NOTICE OF CHANGE

INCH-POUND

MIL-HDBK-5H
NOTICE 1
1 October 2001

DEPARTMENT OF DEFENSE HANDBOOK

METALLIC MATERIALS AND ELEMENTS FOR AEROSPACE VEHICLE STRUCTURES

TO ALL HOLDERS OF MIL-HDBK-5H:

1. THE INSTRUCTIONS FOR CHANGE NOTICE 1 REVISIONS TO MIL-HDBK-5H FOLLOW:

Remove Pages	Insert New Pages from 1 October 2001 Transmittal	Insert Pages Dated 1 December 1998 Reprinted Without Change
Self-cover & ii	Self-cover & ii	
iii	iii/iv	
I thru VIII	I thru VIII	
1-1 thru 1-40	1-1 thru 1-40	—
2-7 & 2-8	2-7 & 2-8	—
2-15 thru 2-18	2-16 thru 2-18	2-15
2-19 thru 2-26	2-19 & 2-20, 2-22 thru 2-26	2-21
2-31 thru 2-40	2-32 thru 2-39	2-31, 2-40
2-45 thru 2-64	2-46 thru 2-55, 2-57 thru 2-61, 2-63	2-45, 2-56, 2-62, 2-64
2-69 & 2-70	2-69	2-70
2-79 thru 2-82	2-80, 2-81	2-79, 2-82
2-93 thru 2-96	2-94, 2-96	2-93, 2-95
2-109 & 2-110	2-109	2-110
2-123 thru 2-126	2-123 thru 2-126	—
2-153 & 2-154	2-153	2-154

AMSC: N/A FSC 1560

Remove Pages	Insert New Pages from 1 October 2001 Transmittal	Insert Pages Dated 1 December 1998 Reprinted Without Change
2-159 thru 2-164	2-159 thru 2-161, 2-163	2-162, 2-164
2-169 & 2-170	2-169	2-170
2-185 thru 2-188	2-185, 2-187 & 2-188	2-186
2-193 & 2-194	2-193	2-194
2-201 & 2-202	2-202	2-201
2-215 thru 2-218	2-216 thru 2-218	2-215
3-11 thru 3-16	3-11 thru 3-16	—
3-17 thru 3-26	3-18 thru 3-24, 3-26	3-17, 3-25
3-31 thru 3-34	3-32 thru 3-34	3-31
3-59 thru 3-64	3-60, 3-61, 3-63 & 3-64	3-59, 3-62
3-67 & 3-68	3-67	3-68
3-71 & 3-72	3-71 & 3-72	—
3-81 thru 3-86	3-81 thru 3-84, 3-85	3-86
3-93 & 3-94	3-94	3-93
3-97 & 3-98	3-98	3-97
3-111 thru 3-124	3-112 thru 3-114, 3-116 thru 3-119, 3-121, 3-123	3-111, 3-115, 3-120, 3-122, 3-124
3-127 & 3-128	3-128	3-127
3-131 & 3-132	3-132	3-131
3-145 & 3-146	3-145	3-146
3-149 & 3-150	3-150	3-149
3-155 & 3-156	3-156	3-155
3-163 thru 3-166	3-164, 3-165	3-163, 3-166
3-169 & 3-170	3-170	3-169
3-193 thru 3-206	3-192a thru 3-206	—
3-253 thru 3-256	3-253, 3-255 & 3-256	3-254
3-259 & 3-260	3-259 & 3-260	—

Remove Pages	Insert New Pages from 1 October 2001 Transmittal	Insert Pages Dated 1 December 1998 Reprinted Without Change
3-279 & 3-282	3-279, 3-281 & 3-282	3-280
3-289 thru 3-462	3-288a thru 3-462	—
3-485 & 3-486	3-485	3-486
3-503 thru 3-506	3-503 thru 3-506	—
4-1 & 4-2	4-2	4-1
4-15 & 4-16	4-16	4-15
4-23 thru 4-28	4-24 thru 4-28	4-23
4-29 & 4-30	4-30	4-29
4-33 & 4-34	4-33 & 4-34	—
4-45 & 4-46	4-45	4-46
5-1 thru 5-4	5-1 thru 5-3	5-4
5-5 thru 5-8	5-6, 5-8	5-5, 5-7
5-15 thru 5-20	5-15 thru 5-19	5-20
5-45 & 5-46	5-45	5-46
5-59 & 5-60	5-59	5-60
5-73 & 5-74	5-73	5-74
5-85 & 5-86	5-85	5-86
5-89 thru 5-92	5-89, 5-92	5-90, 5-91
5-95 & 5-96	5-95 & 5-96	—
5-99 & 5-100	5-99	5-100
5-111 & 5-112	5-111a thru 5-111h	5-111 & 5-112
5-131 & 5-132	5-132	5-131
5-135 & 5-136	5-135	5-136
5-140 & 5-141	5-140 & 5-141	—
6-3 thru 6-6	6-3, 6-6	6-4, 6-5
6-51 thru 6-54	6-52, 6-53	6-51, 6-54

Remove Pages	Insert New Pages from 1 October 2001 Transmittal	Insert Pages Dated 1 December 1998 Reprinted Without Change
6-61 & 6-62	6-61	6-62
6-95 thru 6-96	6-95a thru 6-95f	6-95 & 6-96
6-119 & 6-120	6-120	6-119
7-11 thru 7-14	7-12, 7-13	7-11, 7-14
7-21 & 7-22	7-21 & 7-22	—
7-33 & 7-34	7-33	7-34
7-37 thru 7-40	7-38, 7-39	7-37, 7-40
8-3 thru 8-6b	8-4 thru 8-6b	8-3
8-9 thru 8-14	8-9, 8-11, 8-13	8-10, 8-12, 8-14
8-29 & 8-30	8-29	8-30
8-33 & 8-34	8-33a & 8-33b	8-33 & 8-34
8-51 thru 8-56	8-51 thru 8-54, 8-56	8-55
—	8-56a thru 8-56f	—
8-63 & 8-64	8-64	8-63
8-71 & 8-72	8-72	8-71
8-79 thru 8-82	8-79 thru 8-82	—
—	8-86a thru 8-86h	—
8-87 & 8-88	8-88	8-87
8-121 & 8-122	8-122	8-121
8-129 & 8-130	8-129	8-130
9-1 thru 9-14	9-1 thru 9-4f, 9-5a & 9-5b, 9-7 thru 9-7b, 9-8, 9-10, 9-12, 9-13	9-5, 9-6, 9-9, 9-11, 9-14
9-17 thru 9-18	9-18 thru 9-18b	9-17
9-25 thru 9-32	9-25 thru 9-31b	9-32
9-51 & 9-52	9-52	9-51
9-59 & 9-60	9-60	9-59
9-63 & 9-64	9-63 & 9-64	—
9-133 & 9-134	9-134	9-133

Remove Pages	Insert New Pages from 1 October 2001 Transmittal	Insert Pages Dated 1 December 1998 Reprinted Without Change
9-141 & 9-142	9-141	9-142
9-145 & 9-146	9-146	9-145
9-171 thru 9-174	9-171, 9-174	9-172, 9-173
9-193 & 9-194	9-194	9-193
9-213 thru 9-218	9-213 thru 9-217f	9-218
9-223 & 9-224	9-223	9-224
9-227 thru 9-234	9-227 thru 9-233	9-234
9-239 & 9-240	9-239	9-240
9-255 & 9-256	9-255	9-256
9-257 & 9-258	9-258	9-257
A-15 & A-16	A-16	A-15
B-1 thru B-8	B-1 thru B-8	—
C-1 thru C-8	C-1 thru C-8	—
D-1 thru D-4	D-1 thru D-4	—
E-1 thru E-24	E-1 thru E-12	—.

2. A summary-sheet of technical changes made to MIL-HDBK-5H is appended to this transmittal notice.

3. RETAIN THIS NOTICE AND INSERT BEFORE MIL-HDBK-5H TABLE OF CONTENTS.

4. Holders of MIL-HDBK-5H will verify that the changes indicated above have been made. This notice page will be retained as a check sheet. Activities which stock this notice for issue are advised that this is a separate publication to be retained until a complete revision of MIL-HDBK-5H is made.

5. Holders of MIL-HDBK-5H may wish to retain obsolete pages, replaced by each change notice, to maintain a record of design allowables in effect in previous years.

Custodians:
Army – AV
Navy – AS
Air Force – 11

Preparing activity:
Air Force – 11
(Project 1560-0017)

Review activities:
Army – MI
Navy – CG
Air Force – 84, 99

Civil Agency Coordinating Activity:
FAA

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ANNOTATION OF MIL-HDBK-5H, CHANGE NOTICE 1 REVISIONS

Page	Code[1]	Remarks
Chapter 1		
Self-cover thru VIII	R	Replaced coverpage and foreword
1-1 - 1-40	R	Replaced Chapter 1 with the new revised Chapter 1
Chapter 2		
2-7	R	Revision to Table 2.2.1.0(a)
2-8	R	Revision to Table 2.2.1.0(b)
2-16	R	Revisions to Tables 2.3.1.0(a) and 2.3.1.0(b)
2-17	E	Editorial
2-18	E	MIL spec. converted to AMS specification
2-19	E	Editorial, MIL spec. converted to AMS spec, noncurrent
2-20	R	Revision to Table 2.3.1.0(c_4)
2-22	R	Revisions to Table 2.3.1.0(f_1)
2-23	R	Revision to Table 2.3.1.0(f_2)
2-24	D	Deleted Table 2.3.1.0(g)
2-25	E	Revised thickness to match spec., converted MIL spec to AMS spec.
2-26	R	Table 2.3.1.0(h2)
2-32	E	Replaced scanned image of Figure 2.3.1.2.8(a) with electronic bitmap image
2-33	E	Replaced scanned image of Figure 2.3.1.2.8(b) with electronic bitmap image
2-34	E	Replaced scanned image of Figure 2.3.1.2.8(c) with electronic bitmap image
2-35	E	Replaced image of Figure 2.3.1.2.8(d) with electronic image
2-36	E	Replaced scanned image of Figure 2.3.1.2.8(e) with electronic bitmap image

[1] A - Addition, D-Deletion, E-Editorial correction, R-Revision

2-37	E	Replaced scanned image of Figure 2.3.1.2.8(f) with electronic bitmap image
2-38	E	Replaced scanned image of Figure 2.3.1.2.8(g) with electronic bitmap image
2-39	E	Replaced scanned image of Figure 2.3.1.2.8(h) with electronic bitmap image
2-46	E	Replaced scanned image of Figure 2.3.1.3.8(a) with electronic bitmap image
2-47	E	Replaced scanned image of Figure 2.3.1.3.8(b) with electronic bitmap image, and corrected title
2-48	E	Replaced scanned image of Figure 2.3.1.3.8(c) with electronic bitmap image. Added Std. Error of Est.
2-49	E	Replaced scanned image of Figure 2.3.1.3.8(d) with electronic bitmap image, and corrected title
2-50	E	Replaced scanned image of Figure 2.3.1.3.8(e) with electronic bitmap image
2-51	E	Replaced scanned image of Figure 2.3.1.3.8(f) with electronic bitmap image
2-52	E	Replaced scanned image of Figure 2.3.1.3.8(g) with electronic bitmap image
2-53	E	Replaced scanned image of Figure 2.3.1.3.8(h) with electronic bitmap image
2-54	E	Replaced scanned image of Figure 2.3.1.3.8(i) with electronic bitmap image
2-55	E	Replaced scanned image of Figure 2.3.1.3.8(j) with electronic bitmap image
2-57	E	Replaced scanned image of Figure 2.3.1.8(l) with electronic bitmap image
2-58	E	Replaced scanned image of Figure 2.3.1.3.8(m) with electronic bitmap image
2-59	E	Replaced scanned image of Figure 2.3.1.3.8(n) with electronic bitmap image
2-60	E	Added Std. Deviation
2-61	E & R	Added Std. Error of Estimate and corrected Std. Deviation
2-63	E & R	Added Std. Error of Estimate and corrected Std. Deviation
2-69	E	Editorial
2-80	E	Specification change
2-81	R	Revision to Table 2.4.3.0(b)
2-94	R	Revision to Table 2.5.1.0(a)

2-96	R	Revision to Table 2.5.1.0(c)
2-109	R	Revision to Table 2.5.3.0(b)
2-123	R	Revision to Table 2.6.2.0(b)
2-124	E	Corrected thickness
2-125	R	Revision to Table 2.6.2.0(d)
2-126	E	Corrected thickness
2-153	E	Editorial
2-159	E	Replaced scanned image of Figure 2.6.5.1.8(a) with electronic bitmap image
2-160	E	Replaced image of Figure 2.6.5.1.8(b) and added Std. Deviation
2-161	E	Replaced scanned image of Figure 2.6.5.1.8(c) with electronic bitmap image
2-163	R	Revision to Table 2.6.6.0(b)
2-169	E	Corrected Figure 2.6.6.1.6(a)
2-185	R	Corrected Std. Deviation
2-187	E	Replaced scanned image of Figure 2.6.7.1.8(e) with electronic bitmap image
2-188	E	Corrected properties
2-193	E	Editorial
2-202	E	Corrected Figure 2.6.8.2.6(a)
2-216	R	Revision to Table 2.7.1.0(a)
2-217	R	Revision to Table 2.7.1.0(b)
2-218	R	Revision to Figure 2.7.1.0

Chapter 3

3-11 - 3-13	R	Added data and footnote to Table 3.1.2.1.6
3-14	R	Revision to Section 3.1.2.3.1
3-15	R	Updated list of alloys in Table 3.1.2.3.1(a)
3-16	R	Revision to footnote in Table 3.1.2.3.1(a)

3-18 - 3-21	E	Editorial
3-22	E	Text shifted from page 3-14
3-23	E	Text shifted from page 3-22
3-24	E	Editorial
3-26	R	Revision to Section 3.2.1.0
3-32 & 3-33	E	Editorial, converted MIL spec to AMS spec
3-34	E	Editorial
3-60	E	Replaced scanned image of Figure 3.2.1.1.8(b) with electronic bitmap image
3-61	E & R	Replaced scanned image of Figure 3.2.1.1.8(c) with electronic bitmap image and corrected R^2 value
3-63	E	Replaced scanned image of Figure 3.2.1.1.8(e) with electronic bitmap image. Removed caution statement.
3-64	E	Revised Figure 3.2.2.0
3-67	R	Revision to Section 3.2.3.0
3-71 - 3-72	E	Footnote order
3-81	E	Editorial change to Table 3.2.3.0(i_1)
3-82	E	Editorial
3-83	E	Corrected specification
3-84	E	Editorial change to Table 3.2.3.0(j_1)
3-85	E	Editorial
3-94	E	Corrected caption to Figure 3.2.3.1.6(b)
3-98	E	Corrected Figures 3.2.3.1.6(i) and (j)
3-112	E	Replaced scanned image of Figure 3.2.3.1.8(b) with electronic bitmap image
3-113	E	Replaced scanned image of Figure 3.2.3.1.8(c) with electronic bitmap image
3-114	E	Replaced scanned image of Figure 3.2.3.1.8(d) with electronic bitmap image
3-116	E	Replaced scanned image of Figure 3.2.3.1.8(f) with electronic bitmap image

3-117	E	Replaced scanned image of Figure 3.2.3.1.8(g) with electronic bitmap image
3-118	E	Replaced scanned image of Figure 3.2.3.1.8(h) with electronic bitmap image
3-119	E	Replaced scanned image of Figure 3.2.3.1.8(i) with electronic bitmap image
3-121	E	Editorial corrections to Figures 3.2.3.3.1(c) and (d)
3-123	E	Editorial correction to Figure 3.2.3.3.6(a)
3-128	E	Editorial corrections to Figures 3.2.3.4.1(c) and (d)
3-132	E	Editorial correction to Figure 3.2.3.4.5(b)
3-145	E	Editorial correction to Figure 3.2.3.5.5(b)
3-150	E	Replaced footnote
3-156	E	Editorial
3-164	R	Revision to Section 3.2.7.0
3-165	E	Text shifted from page 3-164
3-170	E	Editorial
3-192a	A	Added Section 3.2.8
3-192b	A	Added Table 3.2.8.0(b_1)
3-192c	A	Added Table 3.2.8.0(b_2)
3-192d	A	Added blank page
3-193 - 3-197	R	Section number changed
3-197a	A	Added Figures 3.2.10.1.6(a) and 3.2.10.1.6(b)
3-197b	A	Added Figure 3.2.10.1.6(c)
3-198 - 3-206	R	Section number changed, MIL specs. converted to AMS specs.
3-253	E	Editorial
3-255	E	MIL specs. converted to AMS specs.
3-256	E	Editorial
3-259	E	MIL specs. converted to AMS specs.

3-260	E	Editorial
3-279	E	Editorial, MIL spec converted to AMS spec
3-281	E	Editorial change in Section 3.7.1.0
3-282	E	Editorial
3-288a	A	Added Section 3.7.2
3-288b	A	Added Table 3.7.2.0(b_1)
3-288c	A	Added Figure 3.7.2.0
3-288d	A	Blank page added for copying purposes
3-289 - 3-306	E	Section number changed, MIL specs. converted to AMS specs.
3-307	E & R	Section number changed and revision to Section 3.7.4.2
3-308	R	Revised Table 3.7.3.0(b_1) and section number changed
3-309 - 3-311	E	Section number changed
3-312	R & E	Revised Table 3.7.3.0(c_2) and section number changed
3-313 - 3-326	E	Section number changed
3-327	E & R	Section number changed and revision to Figure 3.7.4.2.8(a) caption
3-327a	A	Added Figure 3.7.4.2.8(b)
3-327b	A	Added Figure 3.7.4.2.8(c)
3-327c	A	Added Figure 3.7.4.2.8(d)
3-327d	A	Added Information for Figure 3.7.4.2.8(d)
3-328	E & R	Section number changed and revision to Figure 3.7.4.2.8(e) caption
3-329	E & R	Section number changed and revision to Figure 3.7.4.2.8(f) caption
3-330	E & R	Section number changed and revision to Figure 3.7.4.2.8(g) caption
3-331	E & R	Section number changed and revision to Figure 3.7.4.2.8(h) caption
3-332	E & R	Section number changed and revision to Figure 3.7.4.2.8(i) caption
3-333	E & R	Section number changed and revision to Figure 3.7.4.2.8(j) caption

3-334	E & R	Section number changed and revision to Figure 3.7.4.2.8(k) caption
3-335	E & R	Section number changed and revision to Figure 3.7.4.2.8(l) caption
3-339	E	Replaced Figures 3.7.4.3.6(a) and (b)
3-336 - 3-343	E	Section number changed
3-343a	A & E	Added Section 3.7.4 and section number changed
3-343b	A & E	Added Table 3.7.4.0(b) and section number changed
3-343c	A & E	Added Table 3.7.4.0(c) and section number changed
3-343d	A	Blank page
3-344	R	Revision to Section 3.7.6.0 and section number changed and revised introductory information
3-345	E	Text shifted from page 3-344
3-346 - 3-386	E	Section number changed, MIL specs. converted to AMS specs.
3-355	E	Editorial
3-373	E	Editorial correction to Figure 3.7.6.1.6(d)
3-382 - 3-384	E	Added Standard Error of Estimate and Standard Deviation
3-385	E	Replaced scanned image
3-387	E & R	Section number changed. Replaced scanned image of Figure 3.7.3.1.8(f) with electronic bitmap image and corrected R^2
3-388 - 3-406	E	Section number changed
3-389	E	Replaced scanned image
3-405	R	Revised Table 3.7.7.0(b_2)
3-407	R & E	Revised Table 3.7.6.0(c_2) and section number changed
3-408 - 3-454	E	Section number changed
3-412	E	Replaced scanned image and added Standard Deviation
3-413	E	Added Standard Deviation
3-414	E	Replaced scanned image and added Standard Deviation

3-417 & 3-418	E	MIL specs. converted to AMS specs.
3-421 - 3-422	E	Replaced scanned image and added Standard Deviation
3-423	R	Corrected equivalent stress equation
3-424	E	Added Standard Deviation
3-425	E	Corrected Ramberg Osgood number in Figure 3.7.8.2.6(b)
3-428 - 3-429	E	Added Standard Deviation
3-444	E	Replaced image
3-455	E	Section number changed. Corrected call out for Figure 3.7.8.3.6(c). Editorial change in caption for Figure 3.7.8.3.6(d) and added tangent-modulus line.
3-456 - 3-461	E	Section number changed
3-462	E	MIL spec. converted to AMS spec.
3-485	E	Editorial, MIL spec. converted to AMS spec.
3-503	E	Reference numbers changed due to revised section numbers
3-504	E & A	Reference numbers changed due to revised section numbers and added References 3.7.4.2.8(d) and (e)
3-505	E	Reference numbers changed due to revised section numbers
3-506	E	Reference numbers changed due to revised section numbers

Chapter 4

4-2	E	Editorial
4-16	E	Replaced scanned image of Figure 4.2.1.4.8(a) with electronic bitmap image
4-24 - 4-26	E	Replaced Figures 4.2.3.2.8(a)-(c)
4-27 & 4-28	R	Revision to Tables 4.3.1.0(a) and 4.3.1.0(b)
4-30	E	Editorial
4-33 & 4-34	R	Revision to Tables 4.3.3.0(a) and 4.3.3.0(b)
4-45	E	Editorial

Chapter 5

5-1	R	Revised Table 5.1
5-2 & 5-3	E	Text shift, noted spec. as inactive
5-3 & 5-5	E	Removed reference to inactive spec. MIL-S-5002
5-6	R	Specification converted from MIL to AMS
5-8	R	Specification converted from MIL to AMS
5-15	E	Removed reference to inactive spec. MIL-S-5002
5-16	R	Specification converted from MIL to AMS
5-17	E	Editorial, MIL spec. converted to AMS spec.
5-18	E	Editorial
5-19	R	Specification converted from MIL to AMS
5-45	E	Editorial, Specification converted from MIL to AMS
5-59	E	Editorial
5-73	E	Editorial change in Equivalent strain equation
5-85	E	Editorial
5-89	R	Corrected Std. Error of Estimate
5-92	R	Corrected Maximum Stress equation
5-95 & 5-96	R	Specification converted from MIL to AMS
5-99	R	Specification converted from MIL to AMS
5-111a-h	A	Add new section 5.4.3
5-132	E	Replaced existing Figures 5.5.2.1.6(a) and (b) with correct figures
5-135	E	Editorial
5-140	A	Added reference
5-141	E	Rolled over from previous page

Chapter 6

6-3	A	Added notation to Reference 6.1.1.1
6-6	E	Editorial
6-52	E	Editorial
6-53	E	Editorial
6-61	E	Editorial change in 0.10 percent creep equation. Added R^2.
6-95a	A	Added Section 6.3.9
6-95b	A	Added Table 6.3.9.0(b)
6-95c	A	Added Table 6.3.9.0(c)
6-95d	A	Added Figures 6.3.9.0(a) and (b)
6-95e	A	Added Figures 6.3.9.0(c) and (d)
6-95f	A	Added Figure 6.3.9.0(e)
6-120	A	Added Reference 6.1.1.1

Chapter 7

7-12 & 7-13	R	Revision to Tables 7.3.2.0(b) and 7.3.2.0(c)
7-21 & 7-22	E	Editorial
7-33	E	Editorial
7-38 - 7-39	R	Revised Figures 7.5.1.1.6(i)-(l)

Chapter 8

8-4	A	Added to existing Table 8.1.1(a)
8-5	A & D	Added and deleted Fastener Identification to existing Table 8.1.1(b). Page ending changed.
8-6	A & D	Added and deleted Fastener Identification to existing Table 8.1.1(b). Page ending changed.
8-6a	E	Text shifted from page 8-6
8-6b	E	Blank page inserted for copying purposes

8-9	R	Revised wording for Section 8.1.2
8-11	E	Editorial
8-13	E	Editorial change to Table 8.1.2.1(b)
8-29	E	Corrected ultimate strength values for 0.08" and 0.09" sheet thickness, 3/16 in. rivet
8-33a	A	Added Table 8.1.2.2(t)
8-33b	A	Blank page added for copying purposes
8-51	D	Deleted Table 8.1.3.1.2(k)
8-52	D	Deleted Table 8.1.3.1.2(l)
8-53	R	Replaced Table 8.1.3.1.2(m)
8-54	R	Replaced Table 8.1.3.1.2(n)
8-56	E	Corrected yield strength value (to not exceed ultimate) for 0.190" sheet thickness, 5/32 inch rivet
8-56a	A	Added Table 8.1.3.1.2(q)
8-56b	A	Added Table 8.1.3.1.2(r)
8-56c	A	Added Table 8.1.3.1.2(s)
8-56d	A	Added Table 8.1.3.1.2(t)
8-56e	A	Added Table 8.1.3.1.2(u)
8-56f	A	Added Table 8.1.3.1.2(v)
8-64	E	Corrected yield strength value for 0.100" sheet thickness, 1/4 inch rivet
8-72	R	Replaced Table 8.1.3.2.2(g)
8-79	E	Editorial
8-80	D	Deleted Table 8.1.3.2.2(o)
8-81	D	Deleted Table 8.1.3.2.2(p)
8-82	R	Replaced Table 8.1.3.2.2(q)
8-86a	A	Added Table 8.1.3.2.2(v)

8-86b	A	Added Table 8.1.3.2.2(w)
8-86c	A	Added Table 8.1.3.2.2(x)
8-86d	A	Added Table 8.1.3.2.2(y)
8-86e	A	Added Table 8.1.3.2.2(z)
8-86f	A	Added Table 8.1.3.2.2(aa)
8-86g	A	Added Table 8.1.3.2.2(bb)
8-86h	A	Added Table 8.1.3.2.2(cc)
8-88	E	Corrected specification in footnote
8-122	E	Corrected several rivet yield strength values (to not exceed ultimate)
8-129	E	Corrected 0.312" rivet yield strength values

Chapter 9

9-1	A	Added new section 9.0.1 and 9.0.2
9-2	E	Replaced “normal” with “Pearson”
9-3	E	Text shifted from 9-4
9-4	A	Added new section 9.0.1 and 9.0.2
9-4a, b	A	Added Table 9.0.1
9-4c-e	A	Added Table 9.0.2
9-4f	A	Blank page
9-5a	R	Added text to Section 9.1.4
9-5b	A	Added page for copying purposes
9-7	R	Added text to Section 9.1.6.1 and modified text in Section 9.1.6.2
9-7a	R	Added text to Section 9.1.6.3
9-7b	A	Added blank page for copying purposes
9-8	R	Modified text in Table 9.1.6
9-10	E & R	Text shifted from previous page 9-10. Added text to Section 9.1.6.4.

9-12	R	Added text to Section 9.1.6.8
9-13	E	Text shifted from previous page 9-12
9-18	R	Added text the Section 9.2.2.1
9-18a	E	Text shifted from previous page 9-18
9-18b	A	Added blank page for copying purposes
9-25	R	Modified text in Section 9.2.4.2
9-26	R	Revisions to Sections 9.2.5 and 9.2.6.1 (Sequential Pearson Procedure). Added text to Section 9.2.6.1.
9-26a	R	Added text to Sections 9.2.6.1 and 9.2.6.2
9-26b	A	Added Table 9.2.6.1 and Figure 9.2.6.1
9-27	D	Deleted Figure 9.2.6
9-27	A	Added Figure 9.2.6(a)
9-27a	A	Added Figure 9.2.6(b)
9-27b	A	Added blank page for copying purposes
9-28	R	Revision to Section 9.2.6.1 (Sequential Pearson Procedure)
9-29	R	Revision to Section 9.2.7.2 Computational Procedure
9-30	R	Revision to Section 9.2.7.2 Computational Procedure
9-31	R	Revision to Section 9.2.7.2 Computational Procedure
9-31a	E	Text shifted from page 9-31
9-31b	E	Blank page inserted
9-52	E	Editorial change to Standard Error of Estimate
9-60	R	Added text to Section 9.2.15
9-63	E	Text shifted from page 9-60
9-64	E	Text shifted from page 9-63
9-134	E	Added Std. Error of Estimate to Correlative Information format

9-141	R	Revised correlative information
9-146	R	Revised correlative information
9-171	R	Changed MIL-STD specification to NASM specification
9-174	R	Changed MIL-STD specification to NASM specification
9-194	R	Changed MIL-STD specification to NASM specification
9-213	E & R	Editorial change to Section 9.6.1.1. Revision to include Pearson information
9-214	D	Deleted paragraph from Section 9.6.1.3
9-215	E	Text shifted from page 9-216
9-215a	A	Added Figure 9.6.1.1
9-215b	A	Blank page
9-216	R & A	Changed text and added text in Section 9.6.1.5
9-216a	A	Added Section 9.6.1.7
9-216b	A	Added Section 9.6.1.8
9-216c	A	Added Section 9.6.1.9
9-216d	A	Continuation of text from Section 9.6.1.9
9-217	E & A	Text shifted from prior page 9-217. Added section 9.6.1.7
9-217a, b	A	Added sections 9.6.1.8 and 9.6.1.9
9-217c	A	Added Figure 9.6.1.5
9-217d	A	Remainder of new section 9.6.1.9
9-217e	A	Added Figure 9.6.1.6
9-217f	A	Blank page
9-223	E	Revised Figure 9.6.3
9-227	R & A	Replaced Equations 9.6.3.2(g) and 9.6.3.2(h) with text. Replaced Section 9.6.3.3
9-228 - 9-233	R	Replaced Section 9.6.3.3

9-239	E	Editorial change to Table 9.6.4.2
9-255	E	Editorial changes to Weibull Threshold, Section 9.6.5.1
9-258	R	Changed MIL-STD specification to NASM specification

Appendix A

A-16	A	Added table of conversion units previously in Chapter 1

Appendix B

B-1 - B-8	E	MIL specs. converted to AMS specs.
B-1	A & E	Added alloy 2424 and changed section numbers. Page ending changed.
B-2	R & E	Revised alloy list for 4340 and changed section numbers. Page ending changed.
B-3	A & E	Added alloys 7040 and 7055 and changed section numbers. Page ending changed.
B-4	D & E	Deleted reference to 8630 sheet, strip and plate. Changed section numbers. Page ending changed.
B-5	R, E, & A	Revised section numbers and alloy AISI 1025. Changed section numbers. Added alloy AISI 301.
B-6	A & E	Added alloy Haynes®230®. Page ending changed.
B-7	E	Page ending changed
B-8	E	Page ending changed

Appendix C

C-1	E	Changed section numbers. Page ending changed.
C-2	E & A	Changed section numbers. Added Specifications 4206, 4211, 4270, 4273, and 4337. Page ending changed.
C-3	E	Page ending changed
C-4	E	Page ending changed

C-5	E & A	Page ending changed. Added Specifications AISI 301 and AMS 5901 and 5902.
C-6	E	Page ending changed
C-7	E	Changed section numbers. Deleted MIL-S-8844 and 8949. Page ending changed. MIL specs. converted to AMS specs.
C-8	E	Changed section numbers. Page ending changed. MIL specs. converted to AMS specs.

Appendix D

D-1 - D-4	E	Updated page number notation to reflect correct page numbers

Appendix E

D-1 - D-12	E	Updated figure index to reflect correct figure form

INCH-POUND

MIL-HDBK-5H
1 December 1998

DEPARTMENT OF DEFENSE
HANDBOOK

METALLIC MATERIALS AND ELEMENTS FOR AEROSPACE VEHICLE STRUCTURES

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FOREWORD

1. This handbook is approved for use by all Departments and Agencies of the Department of Defense and the Federal Aviation Administration.

2. This handbook is for guidance only. This handbook cannot be cited as a requirement. If it is, the contractor does not have to comply.

3. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: Chairman, MIL-HDBK-5 Coordination Activity (937-656-9134 voice, 937-255-4997 fax), AFRL/MLSC, 2179 Twelfth St., Room 122, Wright-Patterson AFB, OH 45433-7718, by using the Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of Chapter 1 or by letter if using the hard copy.

4. This document contains design information on the strength properties of metallic materials and elements for aerospace vehicle structures. All information and data contained in this handbook have been coordinated with the Air Force, Army, Navy, Federal Aviation Administration, and industry prior to publication, and are being maintained as a joint effort of the Department of Defense and the Federal Aviation Administration.

5. The electronic copy of the Handbook is technically consistent with the paper-copy Handbook; however, minor differences exist in format; e.g., table or figure position. Depending on monitor size and resolution setting, more data may be viewed without on-screen magnification. The figures were converted to electronic format using one of several methods. For example, digitization or recomputation methods were used on most of the engineering figures like typical stress-strain and effect of temperature, etc. Scanning was used to capture informational figures such as those found in Chapters 1 and 9, as well as most of the S/N curves and the majority of graphics in Chapters 4 through 7. These electronic figures were also used to generate the paper copy figures to maintain equivalency between the paper copy and electronic copy. In all cases, the electronic figures have been compared to the paper copy figures to ensure the electronic figure was technically equivalent. Appendix E provides a detailed listing of all the figures in the Handbook, along with a description of each figure's format.

EXPLANATION OF NUMERICAL CODE

For chapters containing materials properties, a deci-numeric system is used to identify sections of text, tables, and illustrations. This system is explained in the examples shown below. Variations of this deci-numerical system are also used in Chapters 1, 8, and 9.

Example A — 2.4.2.1.1

Description	Code digit
General material category (in this case, steel)	2
A logical breakdown of the base material by family characteristics (in this case, intermediate alloy steels); or for element properties	4
Particular alloy to which all data are pertinent. If zero, section contains comments on the family characteristics	2
If zero, section contains comments specific to the alloy; if it is an integer, the number identifies a specific temper or condition (heat treatment)	1
Type of graphical data presented on a given figure (see following description)	1

Example B — 3.2.3.1.X

Description	Code digit
Aluminum	3
2000 Series Wrought Alloy	2
2024 Alloy	3
T3, T351, T3510, T3511, T4, and T42 Tempers	1
Specific Property as Follows	X

Property	X
Tensile properties (ultimate and yield strength)	1
Compressive yield and shear ultimate strengths	2
Bearing properties (ultimate and yield strength)	3
Modulus of elasticity, shear modulus	4
Elongation, total strain at failure, and reduction of area	5
Stress-strain curves, tangent-modulus curves	6
Creep	7
Fatigue	8
Fatigue-Crack Propagation	9
Fracture Toughness	10

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CONTENTS

NOTE: Information and data for alloys deleted from MIL-HDBK-5 may be obtained through the Chairman, MIL-HDBK-5 Coordination Activity.

CONTENTS (Continued)

NOTE: Information and data for alloys deleted from MIL-HDBK-5 may be obtained through the Chairman, MIL-HDBK-5 Coordination Activity.

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CHAPTER 1

GENERAL

1.1 PURPOSE AND USE OF DOCUMENT

1.1.1 INTRODUCTION — Since many aerospace companies manufacture both commercial and military products, the standardization of metallic materials design data, which are acceptable to Government procuring or certification agencies is very beneficial to those manufacturers as well as governmental agencies. Although the design requirements for military and commercial products may differ greatly, the required design values for the strength of materials and elements and other needed material characteristics are often identical. Therefore, this publication provides standardized design values and related design information for metallic materials and structural elements used in aerospace structures. The data contained herein, or from approved items in the minutes of MIL-HDBK-5 coordination meetings, are acceptable to the Air Force, the Navy, the Army, and the Federal Aviation Administration. Approval by the procuring or certificating agency must be obtained for the use of design values for products not contained herein.

This printed document is distributed by the Defense Area Printing Service (DAPS). It is the only official form of MIL-HDBK-5. If computerized MIL-HDBK-5 databases are used, caution should be exercised to ensure that the information in these databases is identical to that contained in this Handbook.

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Philadelphia, PA 19111-5094

U.S. Government personnel may also obtain a free electronic copy of the current document from DAPS through the ASSIST website at http://assist.daps.mil.

1.1.2 SCOPE OF HANDBOOK — This Handbook is primarily intended to provide a source of design mechanical and physical properties, and joint allowables. Material property and joint data obtained from tests by material and fastener producers, government agencies, and members of the airframe industry are submitted to MIL-HDBK-5 for review and analysis. Results of these analyses are submitted to the membership during semi-annual coordination meetings for approval and, when approved, published in this Handbook.

This Handbook also contains some useful basic formulas for structural element analysis. However, structural design and analysis are beyond the scope of this Handbook.

References for data and various test methods are listed at the end of each chapter. The reference number corresponds to the applicable paragraph of the chapter cited. Such references are intended to provide sources of additional information, but should not necessarily be considered as containing data suitable for design purposes.

The content of this Handbook is arranged as follows:

Chapter(s)	Subjects
1	Nomenclature, Systems of Units, Formulas, Material Property Definitions, Failure Analysis, Column Analysis, Thin-Walled Sections
2-7	Material Properties
8	Joint Allowables
9	Data Requirements, Statistical Analysis Procedures

1.2 NOMENCLATURE

1.2.1 SYMBOLS AND DEFINITIONS — The various symbols used throughout the Handbook to describe properties of materials, grain directions, test conditions, dimensions, and statistical analysis terminology are included in Appendix A.

1.2.2 INTERNATIONAL SYSTEM OF UNITS (SI) — Design properties and joint allowables contained in this Handbook are given in customary units of U.S. measure to ensure compatibility with government and industry material specifications and current aerospace design practice. Appendix A.4 may be used to assist in the conversion of these units to Standard International (SI) units when desired.

1.3 COMMONLY USED FORMULAS

1.3.1 GENERAL — Formulas provided in the following sections are listed for reference purposes. Sign conventions generally accepted in their use are that quantities associated with tension action (loads, stresses, strains, etc., are usually considered as positive and quantities associated with compressive action are considered as negative. When compressive action is of primary interest, it is sometimes convenient to identify associated properties with a positive sign. Formulas for all statistical computations relating to allowables development are presented in Chapter 9.

1.3.2 SIMPLE UNIT STRESSES —

f_t = P / A (tension) [1.3.2(a)]

f_c = P / A (compression) [1.3.2(b)]

f_b = My / I = M / Z [1.3.2(c)]

f_s = S / A (average direct shear stress) [1.3.2(d)]

f_x = SQ / Ib (longitudinal or transverse shear stress) [1.3.2(e)]

f_x = Ty / I_p (shear stress in round tubes due to torsion) [1.3.2(f)]

f_s = (T/2At) (shear stress due to torsion in thin-walled structures of closed section. Note that A is the area enclosed by the median line of the section.) [1.3.2(g)]

f_A = Bf_H ; f_T = Bf_L [1.3.2(h)]

1.3.3 COMBINED STRESSES (SEE SECTION 1.5.3.5) —

$f_A = f_c + f_b$ (compression and bending) [1.3.3(a)]

$$f_{s\,max} = \left[f_s^2 + (f_n/2)^2\right]^{1/2}$$ (compression, bending, and torsion) [1.3.3(b)]

$f_{n\,max} = f_n/2 + f_{s\,max}$ [1.3.3(c)]

1.3.4 DEFLECTIONS (AXIAL) —

$e = \delta / L$ (unit deformation or strain) [1.3.4(a)]

$E = f/e$ (This equation applied when E is obtained from the same tests in which f and e are measured.) [1.3.4(b)]

$\delta = eL = (f / E)L$ [1.3.4(c)]

$= PL / (AE)$ (This equation applies when the deflection is to be calculated using a known value of E.) [1.3.4(d)]

1.3.5 DEFLECTIONS (BENDING) —

$di/dx = M / (EI)$ (Change of slope per unit length of a beam; radians per unit length) [1.3.5(a)]

$$i_2 = i_1 + \int_{x_1}^{x_2} [M/(EI)]\,dx$$ — Slope at Point 2. (This integral denotes the area under the curve of M/EI plotted against x, between the limits of x_1 and x_2.) 1.3.5(b)]

$$y_2 = y_1 + i(x_2 - x_1) + \int_{x_1}^{x_2} (M / EI)(x_2 - x)\,dx$$ — Deflection at Point 2. [1.3.5(c)]

(This integral denotes the area under the curve having an ordinate equal to M/EI multiplied by the corresponding distances to Point 2, plotted against x, between the limits of x_1 and x_2.)

$$y_2 = y_1 + \int_{x_1}^{x_2} i\,dx$$ — Deflection at Point 2. (This integral denotes the area under the curve of x_1(i) plotted against x, between the limits of x_1 and x_2.) [1.3.5(d)]

1.3.6 DEFLECTIONS (TORSION) —

$d\varphi / dx = / T / (GJ)$ (Change of angular deflection or twist per unit length of a member, radians per unit length.) [1.3.6(a)]

$$\Phi = \int_{x_1}^{x_2} [T / (GJ)]\,dx$$ — Total twist over a length from x_1 to x_2. (This integral denotes the area under the curve of T/GJ plotted against x, between the limits of x_1 and x_2.) [1.3.6(b)]

$\Phi = TL/(GJ)$ (Used when torque T/GJ is constant over length L.) [1.3.6(c)]

1.3.7 BIAXIAL ELASTIC DEFORMATION —

$\mu = e_T/e_L$ (Unit lateral deformation/unit axial deformation.) This identifies Poisson's ratio in uniaxial loading. [1.3.7(a)]

$Ee_x = f_x - \mu f_y$ [1.3.7(b)]

$Ee_y = f_y - \mu f_x$ [1.3.7(c)]

$E_{biaxial} = E(1 - \mu B)$ — B = biaxial elastic modulus. [1.3.7(d)]

1.3.8 BASIC COLUMN FORMULAS —

$F_c = \pi^2 E_t (L' / \rho)^2$ where $L' = L / \sqrt{c}$ — conservative using tangent modulus [1.3.8(a)]

$F_c = \pi^2 E (L' / \rho)^2$ — standard Euler formula [1.3.8(b)]

1.4 BASIC PRINCIPLES

1.4.1 GENERAL — It is assumed that users of this Handbook are familiar with the principles of strength of materials. A brief summary of that subject is presented in the following paragraphs to emphasize principles of importance regarding the use of allowables for various metallic materials.

Requirements for adequate test data have been established to ensure a high degree of reliability for allowables published in this Handbook. Statistical analysis methods, provided in Chapter 9, are standardized and approved by all government regulatory agencies as well as MIL-HDBK-5 members from industry.

1.4.1.1 *Basis* — Primary static design properties are provided for the following conditions:

Tension	F_{tu} and F_{ty}
Compression	F_{cy}
Shear	F_{su}
Bearing	F_{bru} and F_{bry}

These design properties are presented as A- and B- or S-basis room temperature values for each alloy. Design properties for other temperatures, when determined in accordance with Section 1.4.1.3, are regarded as having the same basis as the corresponding room temperature values.

Elongation and reduction of area design properties listed in room temperature property tables represent procurement specification minimum requirements, and are designated as S-values. Elongation and reduction of area at other temperatures, as well as moduli, physical properties, creep properties, fatigue properties and fracture toughness properties are all typical values unless another basis is specifically indicated.

Use of B-Values — The use of B-basis design properties is permitted in design by the Air Force, the Army, the Navy, and the Federal Aviation Administration, subject to certain limitations specified by each agency. Reference should be made to specific requirements of the applicable agency before using B-values in design.

1.4.1.2 *Statistically Calculated Values* — Statistically calculated values are S (since 1975), T_{99} and T_{90}. S, the minimum properties guaranteed in the material specification, are calculated using the same requirements and procedure as AMS and is explained in Chapter 9. T_{99} and T_{90} are the local tolerance bounds, and are defined and may be computed using the data requirements and statistical procedures explained in Chapter 9.

1.4.1.3 *Ratioed Values* — A ratioed design property is one that is determined through its relationship with an established design value. This may be a tensile stress in a different grain direction from the established design property grain direction, or it may be another stress property, e.g., compression, shear or bearing. It may also be the same stress property at a different temperature. Refer to Chapter 9 for specific data requirements and data analysis procedures.

Derived properties are presented in two manners. Room temperature derived properties are presented in tabular form with their baseline design properties. Other than room temperature derived properties are presented in graphical form as percentages of the room temperature value. Percentage values apply to all forms and thicknesses shown in the room temperature design property table for the heat treatment condition indicated therein unless restrictions are otherwise indicated. Percentage curves usually represent short time exposures to temperature (thirty minutes) followed by testing at the same strain rate as used for the room temperature tests. When data are adequate, percentage curves are shown for other exposure times and are appropriately labeled.

1.4.2 STRESS — The term "stress" as used in this Handbook implies a force per unit area and is a measure of the intensity of the force acting on a definite plane passing through a given point (see Equations 1.3.2(a) and 1.3.2(b)). The stress distribution may or may not be uniform, depending on the nature of the loading condition. For example, tensile stresses identified by Equation 1.3.2(a) are considered to be uniform. The bending stress determined from Equation 1.3.2(c) refers to the stress at a specified distance perpendicular to the normal axis. The shear stress acting over the cross section of a member subjected to bending is not uniform. (Equation 1.3.2(d) gives the average shear stress.)

1.4.3 STRAIN — Strain is the change in length per unit length in a member or portion of a member. As in the case of stress, the strain distribution may or may not be uniform in a complex structural element, depending on the nature of the loading condition. Strains usually are present also in directions other that the directions of applied loads.

1.4.3.1 *Poisson's Ratio Effect* — A normal strain is that which is associated with a normal stress; a normal strain occurs in the direction in which its associated normal stress acts. Normal strains that result from an increase in length are designated as positive (+) and those that result in a decrease in length are designated as negative (-).

Under the condition of uniaxial loading, strain varies directly with stress. The ratio of stress to strain has a constant value (E) within the elastic range of the material, but decreases when the proportional limit is exceeded (plastic range). Axial strain is always accompanied by lateral strains of opposite sign in the two directions mutually perpendicular to the axial strain. Under these conditions, the absolute value of a ratio of lateral strain to axial strain is defined as Poisson's ratio. For stresses within the elastic range, this ratio is approximately constant. For stresses exceeding the proportional limit, this ratio is a function of the axial strain and is then referred to as the lateral contraction ratio. Information on the variation of Poisson's ratio with strain and with testing direction is available in Reference 1.4.3.1.

Under multiaxial loading conditions, strains resulting from the application of each directional load are additive. Strains must be calculated for each of the principal directions taking into account each of the principal stresses and Poisson's ratio (see Equations 1.3.7.2 and 1.3.7.3 for biaxial loading).

1.4.3.2 ***Shear Strain*** — When an element of uniform thickness is subjected to pure shear, each side of the element will be displaced in opposite directions. Shear strain is computed by dividing this total displacement by the right angle distance separating the two sides.

1.4.3.3 ***Strain Rate*** — Strain rate is a function of loading rate. Test results are dependent upon strain rate, and the ASTM testing procedures specify appropriate strain rates. Design properties in this Handbook were developed from test data obtained from coupons tested at the stated strain rate or up to a value of 0.01 in./in./min, the standard maximum static rate for tensile testing materials per specification ASTM E 8.

1.4.3.4 ***Elongation and Reduction of Area*** — Elongation and reduction of area are measured in accordance with specification ASTM E 8.

1.4.4 TENSILE PROPERTIES — When a metallic specimen is tested in tension using standard procedures of ASTM E 8, it is customary to plot results as a "stress-strain diagram." Typical tensile stress-strain diagrams are characterized in Figure 1.4.4. Such diagrams, drawn to scale, are provided in appropriate chapters of this Handbook. The general format of such diagrams is to provide a strain scale nondimensionally (in./in.) and a stress scale in 1000 lb/in. (ksi). Properties required for design and structural analysis are discussed in Sections 1.4.4.1 to 1.4.4.6.

1.4.4.1 ***Modulus of Elasticity (E)*** — Referring to Figure 1.4.4, it is noted that the initial part of stress-strain curves are straight lines. This indicates a constant ratio between stress and strain. Numerical values of such ratios are defined as the modulus of elasticity, and denoted by the letter E. This value applies up to the proportional limit stress at which point the initial slope of the stress-strain curve then decreases. Modulus of elasticity has the same units as stress. See Equation 1.3.4 (b).

Other moduli of design importance are tangent modulus, E_t, and secant modulus, E_s. Both of these moduli are functions of strain. Tangent modulus is the instantaneous slope of the stress-strain curve at any selected value of strain. Secant modulus is defined as the ratio of total stress to total strain at any selected value of strain. Both of these moduli are used in structural element designs. Except for materials such as those described with discontinuous behaviors, such as the upper stress-strain curve in Figure 1.4.4, tangent modulus is the lowest value of modulus at any state of strain beyond the proportional limit. Similarly, secant modulus is the highest value of modulus beyond the proportional limit.

Clad aluminum alloys may have two separate modulus of elasticity values, as indicated in the typical stress-strain curve shown in Figure 1.4.4. The initial slope, or primary modulus, denotes a response of both the low-strength cladding and higher-strength core elastic behaviors. This value applies only up to the proportional limit of the cladding. For example, the primary modulus of 2024-T3 clad sheet applies only up to about 6 ksi. Similarly, the primary modulus of 7075-T6 clad sheet applies only up to approximately 12 ksi. A typical use of primary moduli is for low amplitude, high frequency fatigue. Primary moduli are not applicable at higher stress levels. Above the proportional limits of cladding materials, a short transition range occurs while the cladding is developing plastic behavior. The material then exhibits a secondary elastic modulus up to the proportional limit of the core material. This secondary modulus is the slope of the second straight line portion of the stress-strain curve. In some cases, the cladding is so little different from the core material that a single elastic modulus value is used.

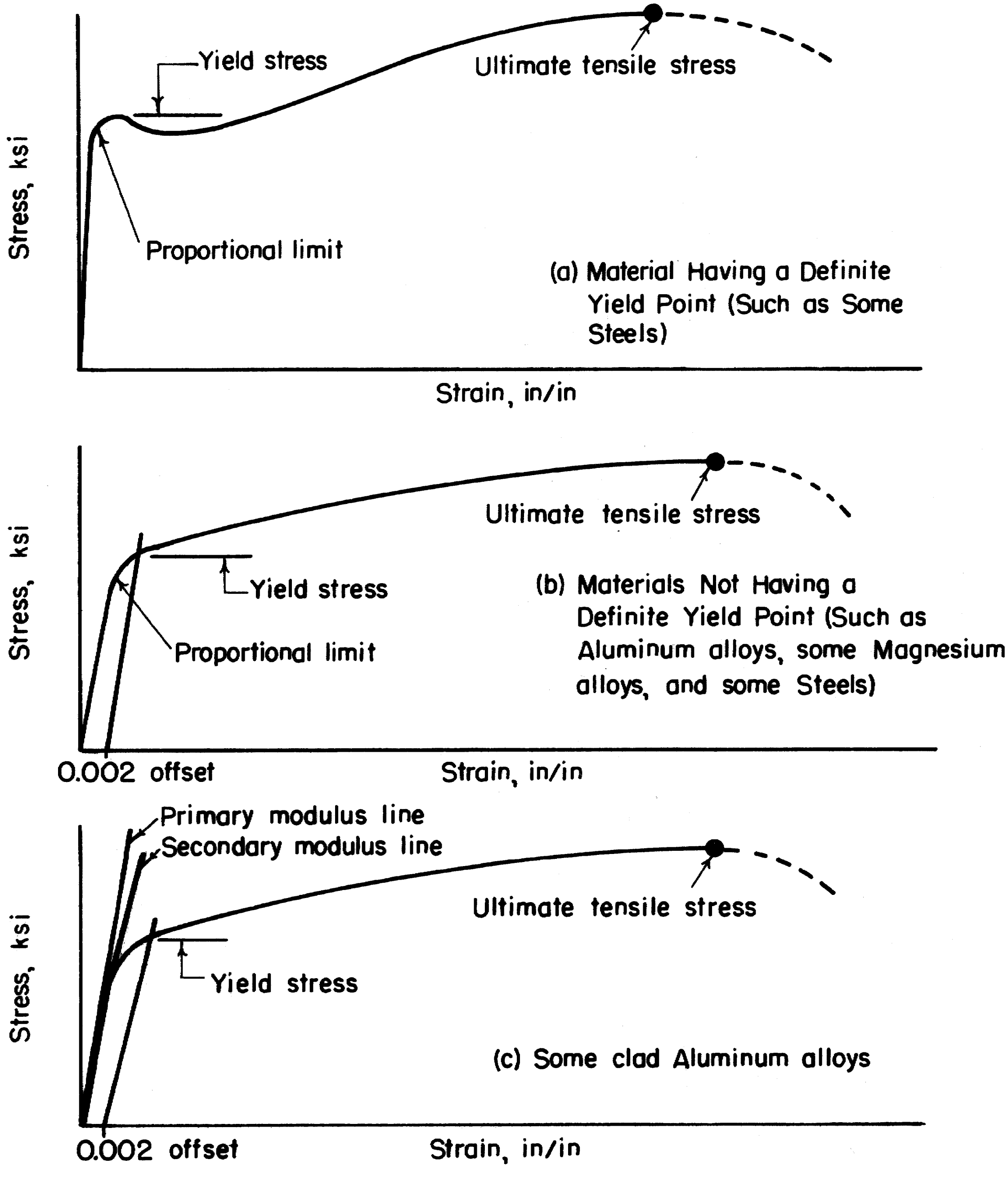

Figure 1.4.4. Typical tensile stress-strain diagrams.

1.4.4.2 ***Tensile Proportional Limit Stress*** **(F_{tp})** — The tensile proportional limit is the maximum stress for which strain remains proportional to stress. Since it is practically impossible to determine precisely this point on a stress-strain curve, it is customary to assign a small value of plastic strain to identify the corresponding stress as the proportional limit. In this Handbook, the tension and compression proportional limit stress corresponds to a plastic strain of 0.0001 in./in.

1.4.4.3 ***Tensile Yield Stress*** **(TYS or F_{ty})** — Stress-strain diagrams for some ferrous alloys exhibit a sharp break at a stress below the tensile ultimate strength. At this critical stress, the material elongates considerably with no apparent change in stress. See the upper stress-strain curve in Figure 1.4.4. The stress at which this occurs is referred to as the yield point. Most nonferrous metallic alloys and most high strength steels do not exhibit this sharp break, but yield in a monotonic manner. This condition is also illustrated in Figure 1.4.4. Permanent deformation may be detrimental, and the industry adopted 0.002 in./in. plastic strain as an arbitrary limit that is considered acceptable by all regulatory agencies. For tension and compression, the corresponding stress at this offset strain is defined as the yield stress (see Figure 1.4.4). This value of plastic axial strain is 0.002 in./in. and the corresponding stress is defined as the yield stress. For practical purposes, yield stress can be determined from a stress-strain diagram by extending a line parallel to the elastic modulus line and offset from the origin by an amount of 0.002 in./in. strain. The yield stress is determined as the intersection of the offset line with the stress-strain curve.

1.4.4.4 ***Tensile Ultimate Stress*** **(TUS or F_{ty})** — Figure 1.4.4 shows how the tensile ultimate stress is determined from a stress-strain diagram. It is simply the maximum stress attained. It should be noted that all stresses are based on the original cross-sectional dimensions of a test specimen, without regard to the lateral contraction due to Poisson's ratio effects. That is, all strains used herein are termed engineering strains as opposed to true strains which take into account actual cross sectional dimensions. Ultimate tensile stress is commonly used as a criterion of the strength of the material for structural design, but it should be recognized that other strength properties may often be more important.

1.4.4.5 ***Elongation (e)*** — An additional property that is determined from tensile tests is elongation. This is a measure of ductility. Elongation, also stated as total elongation, is defined as the permanent increase in gage length, measured after fracture of a tensile specimen. It is commonly expressed as a percentage of the original gage length. Elongation is usually measured over a gage length of 2 inches for rectangular tensile test specimens and in 4D (inches) for round test specimens. Welded test specimens are exceptions. Refer to the applicable material specification for applicable specified gage lengths. Although elongation is widely used as an indicator of ductility, this property can be significantly affected by testing variables, such as thickness, strain rate, and gage length of test specimens. See Section 1.4.1.1 for data basis.

1.4.4.6 ***Reduction of Area (RA)*** — Another property determined from tensile tests is reduction of area, which is also a measure of ductility. Reduction of area is the difference, expressed as a percentage of the original cross sectional area, between the original cross section and the minimum cross sectional area adjacent to the fracture zone of a tested specimen. This property is less affected by testing variables than elongation, but is more difficult to compute on thin section test specimens. See Section 1.4.1.1 for data basis.

1.4.5 COMPRESSIVE PROPERTIES — Results of compression tests completed in accordance with ASTM E 9 are plotted as stress-strain curves similar to those shown for tension in Figure 1.4.4. Preceding remarks concerning tensile properties of materials, except for ultimate stress and elongation, also apply to compressive properties. Moduli are slightly greater in compression for most of the commonly used structural metallic alloys. Special considerations concerning the ultimate compressive stress are described in the following section. An evaluation of techniques for obtaining compressive strength properties of thin sheet materials is outlined in Reference 1.4.5.

1.4.5.1 ***Compressive Ultimate Stress (F_{cu})*** – Since the actual failure mode for the highest tension and compression stress is shear, the maximum compression stress is limited to F_{tu}. The driver for all the analysis of all structure loaded in compression is the slope of the compression stress strain curve, the tangent modulus.

1.4.5.2 ***Compressive Yield Stress (CYS or F_{cy})*** — Compressive yield stress is measured in a manner identical to that done for tensile yield strength. It is defined as the stress corresponding to 0.002 in./in. plastic strain.

1.4.6 SHEAR PROPERTIES — Results of torsion tests on round tubes or round solid sections are plotted as torsion stress-strain diagrams. The shear modulus of elasticity is considered a basic shear property. Other properties, such as the proportional limit stress and shear ultimate stress, cannot be treated as basic shear properties because of "form factor" effects. The theoretical ratio between shear and tensile stress for homogeneous, isotropic materials is 0.577. Reference 1.4.6 contains additional information on this subject.

1.4.6.1 ***Modulus of Rigidity (G)*** — This property is the initial slope of the shear stress-strain curve. It is also referred to as the modulus of elasticity in shear. The relation between this property and the modulus of elasticity in tension is expressed for homogeneous isotropic materials by the following equation:

$$G = \frac{E}{2(1+\mu)} \qquad [1.4.6.1]$$

1.4.6.2 ***Proportional Limit Stress in Shear* (F_{sp})** — This property is of particular interest in connection with formulas which are based on considerations of linear elasticity, as it represents the limiting value of shear stress for which such formulas are applicable. This property cannot be determined directly from torsion tests.

1.4.6.3 ***Yield and Ultimate Stresses in Shear* (SYS or F_{sy}) *and* (SUS or F_{su})** — These properties, as usually obtained from ASTM test procedures tests, are not strictly basic properties, as they will depend on the shape of the test specimen. In such cases, they should be treated as moduli and should not be combined with the same properties obtained from other specimen configuration tests.

Design values reported for shear ultimate stress (F_{su}) in room temperature property tables for aluminum and magnesium thin sheet alloys are based on "punch" shear type tests except when noted. Heavy section test data are based on "pin" tests. Thin aluminum products may be tested to ASTM B 831, which is a slotted shear test (this test is used for other alloys; however, the standard doesn't specifically cover materials other than aluminum). Thicker aluminums use ASTM B 769, otherwise known as the Amsler shear test. These two tests only provide ultimate strength. Shear data for other alloys are obtained from pin tests, except where product thicknesses are insufficient.

1.4.7 BEARING PROPERTIES — Bearing stress limits are of value in the design of mechanically fastened joints and lugs. Only yield and ultimate stresses are obtained from bearing tests. Bearing stress is computed from test data by dividing the load applied to the pin, which bears against the edge of the hole, by the bearing area. Bearing area is the product of the pin diameter and the sheet or plate thickness.

A bearing test requires the use of special cleaning procedures as specified in ASTM E 238. Results are identified as "dry-pin" values. The same tests performed without application of ASTM E 238 cleaning procedures are referred to as "wet pin" tests. Results from such tests can show bearing stresses at least 10 percent lower than those obtained from "dry pin" tests. See Reference 1.4.7 for additional information.

Additionally, ASTM E 238 requires the use of hardened pins that have diameters within 0.001 of the hole diameter. As the clearance increases to 0.001 and greater, the bearing yield and failure stress tends to decrease.

In the definition of bearing values, t is sheet or plate thickness, D is the pin diameter, and e is the edge distance measured from the center of the hole to the adjacent edge of the material being tested in the direction of applied load.

1.4.7.1 *Bearing Yield and Ultimate Stresses (BYS or F_{bry}) and (BUS or F_{bru})* — BUS is the maximum stress withstood by a bearing specimen. BYS is computed from a bearing stress-deformation curve by drawing a line parallel to the initial slope at an offset of 0.02 times the pin diameter.

Tabulated design properties for bearing yield stress (F_{bry}) and bearing ultimate stress (F_{bru}) are provided throughout the Handbook for edge margins of e/D = 1.5 and 2.0. Bearing values for e/D of 1.5 are not intended for designs of e/D < 1.5. Bearing values for e/D < 1.5 must be substantiated by adequate tests, subject to the approval of the procuring or certificating regulatory agency. For edge margins between 1.5 and 2.0, linear interpolation of properties may be used.

Bearing design properties are applicable to t/D ratios from 0.25 to 0.50. Bearing design values for conditions of t/D < 0.25 or t/D > 0.50 must be substantiated by tests. The percentage curves showing temperature effects on bearing stress may be used with both e/D properties of 1.5 and 2.0.

Due to differences in results obtained between dry-pin and wet-pin tests, designers are encouraged to consider the use of a reduction factor with published bearing stresses for use in design.

1.4.8 TEMPERATURE EFFECTS — Temperature effects require additional considerations for static, fatigue and fracture toughness properties. In addition, this subject introduces concerns for time-dependent creep properties.

1.4.8.1 *Low Temperature* — Temperatures below room temperature generally cause an increase in strength properties of metallic alloys. Ductility, fracture toughness, and elongation usually decrease. For specific information, see the applicable chapter and references noted therein.

1.4.8.2 *Elevated Temperature* — Temperatures above room temperature usually cause a decrease in the strength properties of metallic alloys. This decrease is dependent on many factors, such as temperature and the time of exposure which may degrade the heat treatment condition, or cause a metallurgical change. Ductility may increase or decrease with increasing temperature depending on the same variables. Because of this dependence of strength and ductility at elevated temperatures on many variables, it is emphasized that the elevated temperature properties obtained from this Handbook be applied for only those conditions of exposure stated herein.

The effect of temperature on static mechanical properties is shown by a series of graphs of property (as percentages of the room temperature allowable property) versus temperature. Data used to construct these graphs were obtained from tests conducted over a limited range of strain rates. Caution should be exercised in using these static property curves at very high temperatures, particularly if the strain rate intended in design is much less than that stated with the graphs. The reason for this concern is that at very low strain rates or under sustained loads, plastic deformation or creep deformation may occur to the detriment of the intended structural use.

1.4.8.2.1 Creep and Stress-Rupture Properties — Creep is defined as a time-dependent deformation of a material while under an applied load. It is usually regarded as an elevated temperature phenomenon, although some materials creep at room temperature. If permitted to continue indefinitely, creep terminates in rupture. Since creep in service is usually typified by complex conditions of loading and temperature, the number of possible stress-temperature-time profiles is infinite. For economic reasons, creep data for general design use are usually obtained under conditions of constant uniaxial loading and constant temperature in accordance with Reference 1.4.8.2.1(a). Creep data are sometimes obtained under conditions of cyclic uniaxial loading and constant temperature, or constant uniaxial loading and variable temperatures. Section 9.3.6 provides a limited amount of creep data analysis procedures. It is recognized that, when significant creep appears likely to occur, it may be necessary to test under simulated service conditions because of difficulties posed in attempting to extrapolate from simple to complex stress-temperature-time conditions.

Creep damage is cumulative similar to plastic strain resulting from multiple static loadings. This damage may involve significant effects on the temper of heat treated materials, including annealing, and the initiation and growth of cracks or subsurface voids within a material. Such effects are often recognized as reductions in short time strength properties or ductility, or both.

1.4.8.2.2 Creep-Rupture Curve — Results of tests conducted under constant loading and constant temperature are usually plotted as strain versus time up to rupture. A typical plot of this nature is shown in Figure 1.4.8.2.2. Strain includes both the instantaneous deformation due to load application and the plastic strain due to creep. Other definitions and terminology are provided in Section 9.3.6.2.

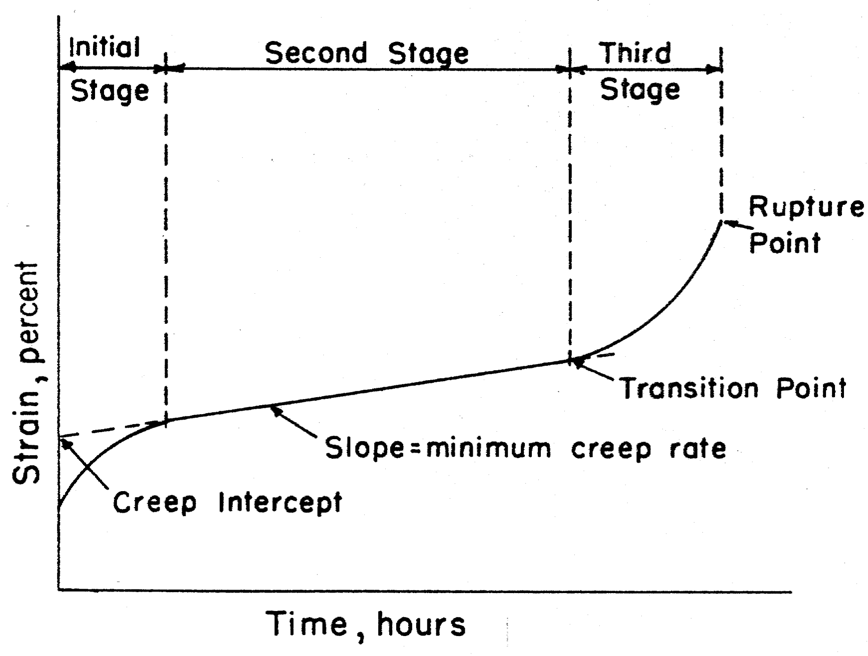

Figure 1.4.8.2.2. Typical creep-rupture curve.

1.4.8.2.3 Creep or Stress-Rupture Presentations — Results of creep or stress-rupture tests conducted over a range of stresses and temperatures are presented as curves of stress versus the logarithm of time to rupture. Each curve represents an average, best-fit description of measured behavior. Modification of such curves into design use are the responsibility of the design community since material applications and regulatory requirements may differ. Refer to Section 9.3.6 for data reduction and presentation methods and References 1.4.8.2.1(b) and (c).

1.4.9 FATIGUE PROPERTIES — Repeated loads are one of the major considerations for design of both commercial and military aircraft structures. Static loading, preceded by cyclic loads of lesser magnitudes, may result in mechanical behaviors (F_{tu} , F_{ty} , etc.) lower than those published in room temperature allowables tables. Such reductions are functions of the material and cyclic loading conditions. A fatigue allowables development philosophy is not presented in this Handbook. However, basic laboratory test data are useful for materials selection. Such data are therefore provided in the appropriate materials sections.

In the past, common methods of obtaining and reporting fatigue data included results obtained from axial loading tests, plate bending tests, rotating bending tests, and torsion tests. Rotating bending tests apply completely reversed (tension-compression) stresses to round cross section specimens. Tests of this type are now seldom conducted for aerospace use and have therefore been dropped from importance in this Handbook. For similar reasons, flexural fatigue data also have been dropped. No significant amount of torsional fatigue data have ever been made available. Axial loading tests, the only type retained in this Handbook, consist of completely reversed loading conditions (mean stress equals zero) and those in which the mean stress was varied to create different stress (or strain) ratios (R = minimum stress or strain divided by maximum stress or strain). Refer to Reference 1.4.9(a) for load control fatigue testing guidelines and Reference 1.4.9(b) for strain control fatigue testing guidelines.

1.4.9.1 *Terminology* — A number of symbols and definitions are commonly used to describe fatigue test conditions, test results and data analysis techniques. The most important of these are described in Section 9.3.4.2.

1.4.9.2 *Graphical Display of Fatigue Data* — Results of axial fatigue tests are reported on S-N and ε - N diagrams. Figure 1.4.9.2(a) shows a family of axial load S-N curves. Data for each curve represents a separate R-value.

S-N and ε - N diagrams are shown in this Handbook with the raw test data plotted for each stress or strain ratio or, in some cases, for a single value of mean stress. A best-fit curve is drawn through the data at each condition. Rationale used to develop best-fit curves and the characterization of all such curves in a single diagram is explained in Section 9.3.4. For load control test data, individual curves are usually based on an equivalent stress which consolidates data for all stress ratios into a single curve. Refer to Figure 1.4.9.2(b). For strain control test data, an equivalent strain consolidation method is used.

Elevated temperature fatigue test data are treated in the same manner as room temperature data, as long as creep is not a significant factor and room temperature analysis methods can be applied. In the limited number of cases where creep strain data have been recorded as a part of an elevated temperature fatigue test series, S-N (or ε - N) plots are constructed for specific creep strain levels. This is provided in addition to the customary plot of maximum stress (or strain) versus cycles to failure.

The above information may not apply directly to the design of structures for several reasons. First, Handbook information may not take into account specific stress concentrations unique to any given structural design. Design considerations usually include stress concentrations caused by reentrant corners, notches, holes, joints, rough surfaces, structural damage, and other conditions. Localized high stresses induced during the fabrication of some parts have a much greater influence on fatigue properties than on static properties.

These factors significantly reduce fatigue life below that which is predictable by estimating smooth specimen fatigue performance with estimated stresses due to fabrication. Fabricated parts have been found to fail at less than 50,000 cycles of loading when the nominal stress was far below that which could be repeated many millions of times using a smooth machined test specimen.

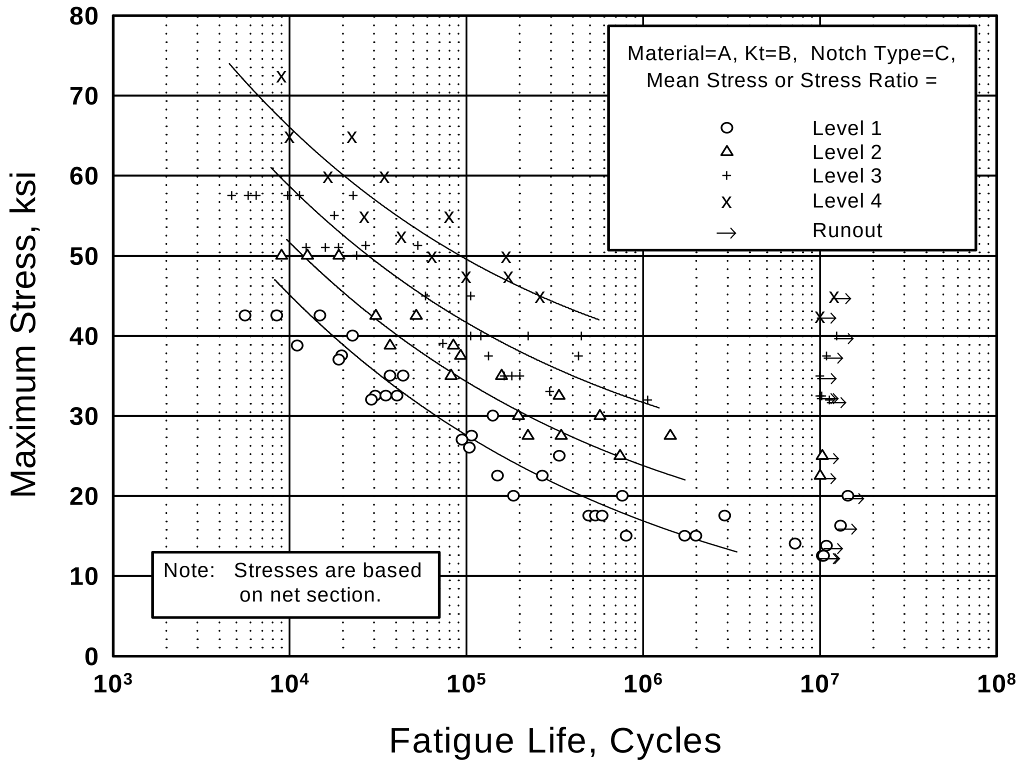

Figure 1.4.9.2(a). Best fit S/N curve diagram for a material at various stress ratios.

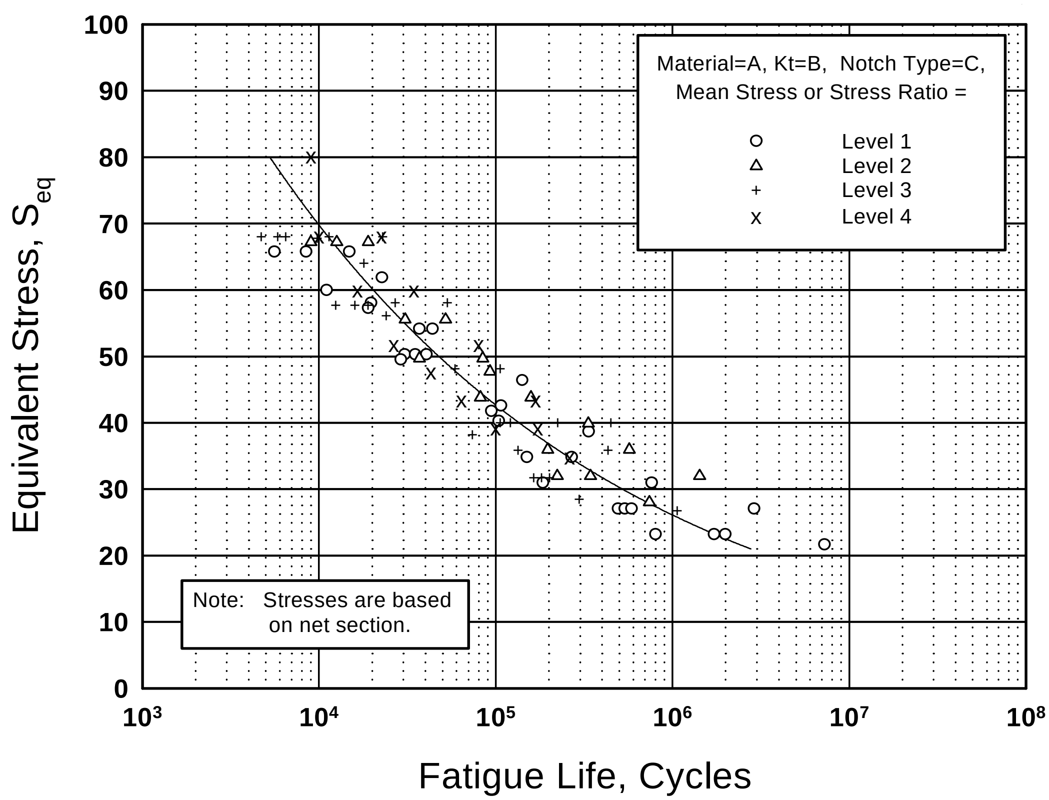

Figure 1.4.9.2(b). Consolidated fatigue data for a material using the equivalent stress parameter.

Notched fatigue specimen test data are shown in various Handbook figures to provide an understanding of deleterious effects relative to results for smooth specimens. All of the mean fatigue curves published in this Handbook, including both the notched fatigue and smooth specimen fatigue curves, require modification into allowables for design use. Such factors may impose a penalty on cyclic life or upon stress. This is a responsibility for the design community. Specific reductions vary between users of such information, and depend on the criticality of application, sources of uncertainty in the analysis, and requirements of the certificating activity. References 1.4.9.2(a) and (b) contain more specific information on fatigue testing procedures, organization of test results, influences of various factors, and design considerations.

1.4.10 METALLURGICAL INSTABILITY — In addition to the retention of strength and ductility, a structural material must also retain surface and internal stability. Surface stability refers to the resistance of the material to oxidizing or corrosive environments. Lack of internal stability is generally manifested (in some ferrous and several other alloys) by carbide precipitation, spheroidization, sigma-phase formation, temper embrittlement, and internal or structural transformation, depending upon the specific conditions of exposure.

Environmental conditions, which influence metallurgical stability include heat, level of stress, oxidizing or corrosive media and nuclear radiation. The effect of environment on the material can be observed as either improvement or deterioration of properties, depending upon the specific imposed conditions. For example, prolonged heating may progressively raise the strength of a metallic alloy as measured on smooth tensile or fatigue specimens. However, at the same time, ductility may be reduced to such an extent that notched tensile or fatigue behavior becomes erratic or unpredictable. The metallurgy of each alloy should be considered in making material selections.

Under normal temperatures, i.e., between -65°F and 160°F, the stability of most structural metallic alloys is relatively independent of exposure time. However, as temperature is increased, the metallurgical instability becomes increasingly time dependent. The factor of exposure time should be considered in design when applicable.

1.4.11 BIAXIAL PROPERTIES — Discussions up to this point pertained to uniaxial conditions of static, fatigue and creep loading. Many structural applications involve both biaxial and triaxial loadings. Because of the difficulties of testing under triaxial loading conditions, few data exist. However, considerable biaxial testing has been conducted and the following paragraphs describe how these results are presented in this Handbook. This does not conflict with data analysis methods presented in Chapter 9. Therein, statistical analysis methodology is presented solely for use in analyzing test data to establish allowables.

If stress axes are defined as being mutually perpendicular along x-, y-, and z-directions in a rectangular coordinate system, a biaxial stress is then defined as a condition in which loads are applied in both of the x- and y-directions. In some special cases, loading may be applied in the z-direction instead of the y-direction. Most of the following discussion will be limited to tensile loadings in the x- and y-directions. Stresses and strains in these directions are referred to as principal stresses and principal strains. See Reference 1.4.11.

When a specimen is tested under biaxial loading conditions, it is customary to plot the results as a biaxial stress-strain diagram. These diagrams are similar to uniaxial stress-strain diagrams shown in Figure 1.4.4. Usually, only the maximum (algebraically larger) principal stress and strain are shown for each test result. When tests of the same material are conducted at different biaxial stress ratios, the resulting curves may be plotted simultaneously, producing a family of biaxial stress-strain curves as shown in Figure 1.4.11 for an isotropic material. For anisotropic materials, biaxial stress-strain curves also require distinction by grain direction.

The reference direction for a biaxial stress ratio, i.e., the direction corresponding to B=0, should be clearly indicated with each result. The reference direction is always considered as the longitudinal (rolling) direction for flat products and the hoop (circumferential) direction for shells of revolution, e.g., tubes, cones, etc. The letter B denotes the ratio of applied stresses in the two loading directions. For example, B-values of 2, 0.5 shown in Figure 1.4.11 indicate results representing both biaxial stress ratios of 2 or 0.5, since this is a hypothetical example for an isotropic material, e.g., cross-rolled sheet. In a similar manner, the curve labeled B=1 indicates a biaxial stress-strain result for equally applied stresses in both directions. The curve labeled $B = \infty$, 0 indicates the biaxial stress-strain behavior when loading is applied in only one direction, e.g., uniaxial behavior. Biaxial property data presented in the Handbook are to be considered as basic material properties obtained from carefully prepared specimens.

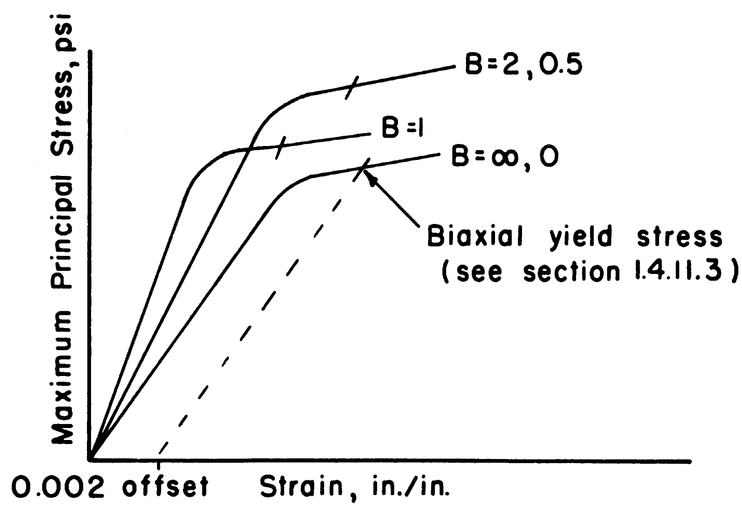

Figure 1.4.11. Typical biaxial stress-strain diagrams for isotropic materials.

1.4.11.1 ***Biaxial Modulus of Elasticity*** — Referring to Figure 1.4.11, it is noted that the original portion of each stress-strain curve is essentially a straight line. In uniaxial tension or compression, the slope of this line is defined as the modulus of elasticity. Under biaxial loading conditions, the initial slope of such curves is defined as the biaxial modulus. It is a function of biaxial stress ratio and Poisson's ratio. See Equation 1.3.7.4.

1.4.11.2 ***Biaxial Yield Stress*** — Biaxial yield stress is defined as the maximum principal stress corresponding to 0.002 in./in. plastic strain in the same direction, as determined from a test curve.

In the design of aerospace structures, biaxial stress ratios other than those normally used in biaxial testing are frequently encountered. Information can be combined into a single diagram to enable interpolations at intermediate biaxial stress ratios, as shown in Figure 1.4.11.2. An envelope is constructed through test results for each tested condition of biaxial stress ratios. In this case, a typical biaxial yield stress envelope is identified. In the preparation of such envelopes, data are first reduced to nondimensional form (percent of uniaxial tensile yield stress in the specified reference direction), then a best-fit curve is fitted through the nondimensionalized data. Biaxial yield strength allowables are then obtained by multiplying the uniaxial F_{ty} (or F_{cy}) allowable by the applicable coordinate of the biaxial stress ratio curve. To avoid possible confusion, the reference direction used for the uniaxial yield strength is indicated on each figure.

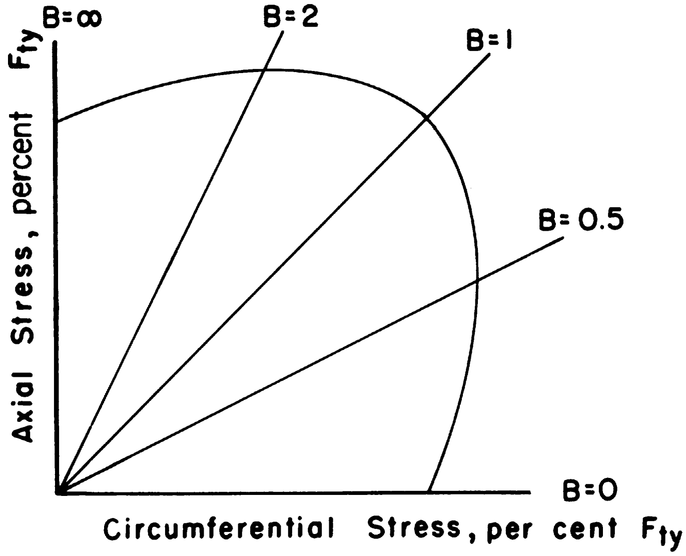

Figure 1.4.11.2. Typical biaxial yield stress envelope.

1.4.11.3 ***Biaxial Ultimate Stress*** — Biaxial ultimate stress is defined as the highest nominal principal stress attained in specimens of a given configuration, tested at a given biaxial stress ratio. This property is highly dependent upon geometric configuration of the test parts. Therefore, such data should be limited in use to the same design configurations.

The method of presenting biaxial ultimate strength data is similar to that described in the preceding section for biaxial yield strength. Both biaxial ultimate strength and corresponding uniform elongation data are reported, when available, as a function of biaxial stress ratio test conditions.

1.4.12 FRACTURE TOUGHNESS — The occurrence of flaws in a structural component is an unavoidable circumstance of material processing, fabrication, or service. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or some combination thereof. The fracture toughness of a part containing a flaw is dependent upon flaw size, component geometry, and a material property defined as fracture toughness. The fracture toughness of a material is literally a measure of its resistance to fracture. As with other mechanical properties, fracture toughness is dependent upon alloy type, processing variables, product form, geometry, temperature, loading rate, and other environmental factors.

This discussion is limited to brittle fracture, which is characteristic of high strength materials under conditions of loading resulting in plane-strain through the cross section. Very thin materials are described as being under the condition of plane-stress. The following descriptions of fracture toughness properties applies to the currently recognized practice of testing specimens under slowly increasing loads. Attendant and interacting conditions of cyclic loading, prolonged static loadings, environmental influences other than temperature, and high strain rate loading are not considered.

1.4.12.1 ***Brittle Fracture*** — For materials that have little capacity for plastic flow, or for flaw and structural configurations, which induce triaxial tension stress states adjacent to the flaw, component behavior is essentially elastic until the fracture stress is reached. Then, a crack propagates from the flaw suddenly and completely through the component. A convenient illustration of brittle fracture is a typical load-compliance record of a brittle structural component containing a flaw, as illustrated in Figure 1.4.12.1. Since little or no plastic effects are noted, this mode is termed brittle fracture.

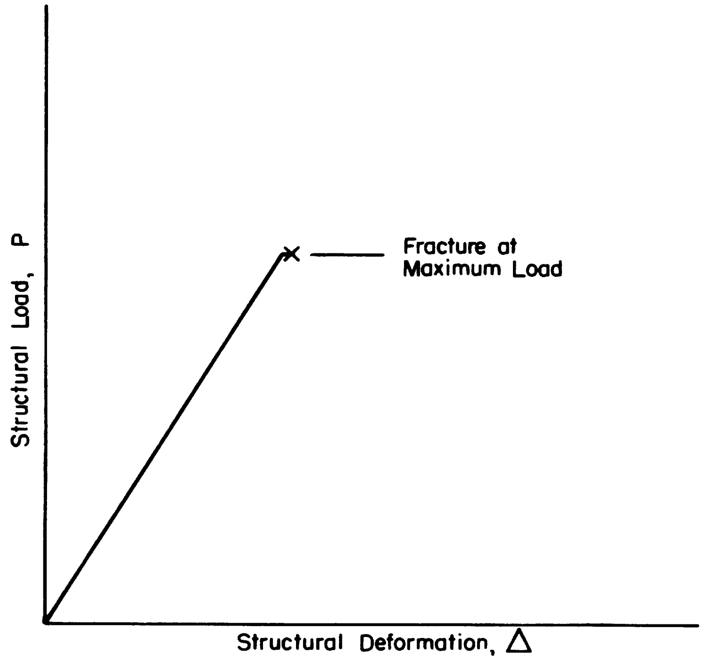

Figure 1.4.12.1. Typical load-deformation record of a structural component containing a flaw subject to brittle fracture.

This mode of fracture is characteristic of the very high-strength metallic materials under plane-strain conditions.

1.4.12.2 ***Brittle Fracture Analysis*** — The application of linear elastic fracture mechanics has led to the stress intensity concept to relate flaw size, component geometry, and fracture toughness. In its very general form, the stress intensity factor, K, can be expressed as

$$K = f\sqrt{a}\,Y, \text{ ksi} \cdot \text{in.}^{1/2} \qquad [1.4.12.2]$$

where

f = stress applied to the gross, flaws section, ksi
a = measure of flaw size, inches
Y = factor relating component geometry and flaw size, nondimensional. See Reference 1.4.12.2(a) for values.

For every structural material, which exhibits brittle fracture (by nature of low ductility or plane-strain stress conditions), there is a lower limiting value of K termed the plane-strain fracture toughness, K_{Ic}.

The specific application of this relationship is dependent on flaw type, structural configuration and type of loading, and a variety of these parameters can interact in a real structure. Flaws may occur through the thickness, may be imbedded as voids or metallurgical inclusions, or may be partial-through (surface) cracks. Loadings of concern may be tension and/or flexure. Structural components may vary in section size and may be reinforced in some manner. The ASTM Committee E 8 on Fatigue and Fracture has developed testing and analytical techniques for many practical situations of flaw occurrence subject to brittle fracture. They are summarized in Reference 1.4.12.2(a).

1.4.12.3 *Critical Plane-Strain Fracture Toughness* — A tabulation of fracture toughness data is printed in the general discussion prefacing most alloy chapters in this Handbook. These critical plane-strain fracture toughness values have been determined in accordance with recommended ASTM testing practices. This information is provided for information purposes only due to limitations in available data quantities and product form coverages. The statistical reliability of these properties is not known. Listed properties generally represent the average value of a series of test results.

Fracture toughness of a material commonly varies with grain direction. When identifying either test results or a general critical plane strain fracture toughness average value, it is customary to specify specimen and crack orientations by an ordered pair of grain direction symbols. The first digit denotes the grain direction normal to the crack plane. The second digit denotes the grain direction parallel to the fracture plane. For flat sections of various products, e.g., plate, extrusions, forgings, etc., in which the three grain directions are designated (L) longitudinal, (T) transverse, and (S) short transverse, the six principal fracture path directions are: L-T, L-S, T-L, T-S, S-L and S-T. Figure 1.4.12.3 identifies these orientations.

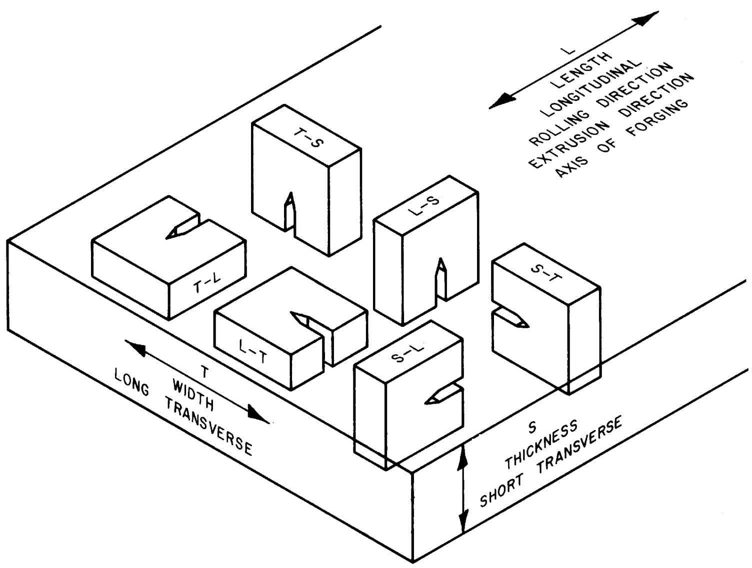

Figure 1.4.12.3. Typical principal fracture path directions.

1.4.12.3.1 *Environmental Effects* — Cyclic loading, even well below the fracture threshold stress, may result in the propagation of flaws, leading to fracture. Strain rates in excess of standard static rates may cause variations in fracture toughness properties. There are significant influences of temperature on fracture toughness properties. Temperature effects data are limited. These information are included in each alloy section, when available.

Under the condition of sustained loading, it has been observed that certain materials exhibit increased flaw propagation tendencies when situated in either aqueous or corrosive environments. When such is known to be the case, appropriate precautionary notes have been included with the standard fracture toughness information.

1.4.12.4 *Fracture in Plane-Stress and Transitional-Stress States* — Plane-strain conditions do not describe the condition of certain structural configurations which are either relatively thin or exhibit appreciable ductility. In these cases, the actual stress state may approach the opposite extreme, plane-stress, or, more generally, some intermediate- or transitional-stress state. The behavior of flaws and cracks under these conditions is different from those of plane-strain. Specifically, under these conditions, significant plastic zones can develop ahead of the crack or flaw tip, and stable extension of the discontinuity occurs as a slow tearing process. This behavior is illustrated in a compliance record by a significant nonlinearity prior to fracture as shown in Figure 1.4.12.4. This nonlinearity results from the alleviation of stress at the crack tip by causing plastic deformation.

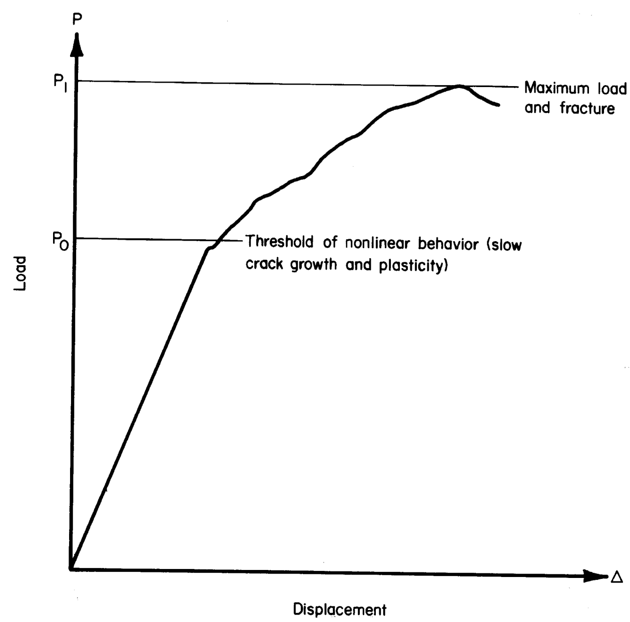

Figure 1.4.12.4. Typical load-deformation record for non-plane strain fracture.

1.4.12.4.1 *Analysis of Plane-Stress and Transitional-Stress State Fracture* — The basic concepts of linear elastic fracture mechanics as used in plane-strain fracture analysis also applies to these conditions. The stress intensity factor concept, as expressed in general form by Equation 1.4.12.2, is used to relate load or stress, flaw size, component geometry, and fracture toughness.

However, interpretation of the critical flaw dimension and corresponding stress has two possibilities. This is illustrated in Figure 1.4.12.4.1. One possibility is the onset of nonlinear displacement with increasing load. The other possibility identifies the fracture condition, usually very close to the maximum load. Generally, these two conditions are separated in applied stress and exhibit large differences in flaw dimensions due to stable tearing.

When a compliance record is transformed into a crack growth curve, the difference between the two possible K-factor designations becomes more apparent. In most practical cases, the definition of nonlinear crack length with increasing load is difficult to assess. As a result, an alternate characterization of this behavior is provided by defining an artificial or "apparent" stress intensity factor.

$$K_{app} = f\sqrt{a_o}\,Y \qquad [1.4.12.4.1]$$

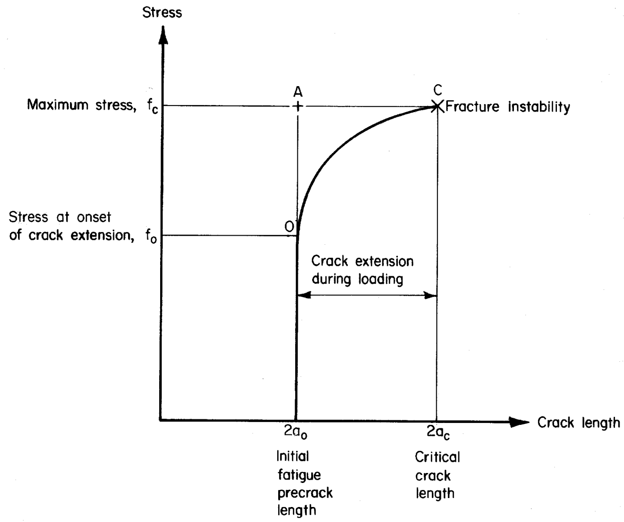

Figure 1.4.12.4.1. Crack growth curve.

The apparent fracture toughness is computed as a function of the maximum stress and initial flaw size. This datum coordinate corresponds to point A in Figure 1.4.12.4.1. This conservative stress intensity factor is a first approximation to the actual property associated with the point of fracture.

1.4.12.5 ***Apparent Fracture Toughness Values for Plane-Stress and Transitional-Stress States*** — When available, each alloy chapter contains graphical formats of stress versus flaw size. This is provided for each temper, product form, grain direction, thickness, and specimen configuration. Data points shown in these graphs represent the initial flaw size and maximum stress achieved. These data have been screened to assure that an elastic instability existed at fracture, consistent with specimen type. The average K_{app} curve, as defined in the following subsections, is shown for each set of data.

1.4.12.5.1 *Middle-Tension Panels* — The calculation of apparent fracture toughness for middle-tension panels is given by the following equation.

$$K_{app} = f_c\left(\pi a_o \cdot \sec \pi a_o / W\right)^{1/2} \qquad [1.4.12.5.1(a)]$$

Data used to compute K_{app} values have been screened to ensure that the net section stress at failure did not exceed 80 percent of the tensile yield strength; that is, they satisfied the criterion:

$$f_c \leq 0.8(TYS) / (1 - 2a / W) \qquad [1.4.12.5.1(b)]$$

This criterion assures that the fracture was an elastic instability and that plastic effects are negligible.

The average K_{app} parametric curve is presented on each figure as a solid line with multiple extensions where width effects are displayed in the data. As added information, where data are available, the propensity for slow stable tearing prior to fracture is indicated by a crack extension ratio, $\Delta 2a/2a_o$. The coefficient (2) indicates the total crack length; the half-crack length is designated by the letter "a." In some cases, where data exist covering a wide range of thicknesses, graphs of K_{app} versus thickness are presented.

1.4.13 FATIGUE CRACK GROWTH — Crack growth deals with material behavior between crack initiation and crack instability. In small size specimens, crack initiation and specimen failure may be nearly synonymous. However, in larger structural components, the existence of a crack does not necessarily imply imminent failure. Significant structural life exists during cyclic loading and crack growth.

1.4.13.1 *Fatigue Crack Growth* — Fatigue crack growth is manifested as the growth or extension of a crack under cyclic loading. This process is primarily controlled by the maximum load or stress ratio. Additional factors include environment, loading frequency, temperature, and grain direction. Certain factors, such as environment and loading frequency, have interactive effects. Environment is important from a potential corrosion viewpoint. Time at stress is another important factor. Standard testing procedures are documented in Reference 1.4.13.1.

Fatigue crack growth data presented herein are based on constant amplitude tests. Crack growth behaviors based on spectrum loading cycles are beyond the scope of this Handbook. Constant amplitude data consist of crack length measurements at corresponding loading cycles. Such data are presented as crack growth curves as shown in Figure 1.4.13.1(a).

Since the crack growth curve is dependent on initial crack length and the loading conditions, the above format is not the most efficient form to present information. The instantaneous slope, $\Delta a/\Delta N$, corresponding to a prescribed number of loading cycles, provides a more fundamental characterization of this behavior. In general, fatigue crack growth rate behavior is evaluated as a function of the applied stress intensity factor range, ΔK, as shown in Figure 1.4.13.1(b).

1.4.13.2 *Fatigue Crack Growth Analysis* — It is known that fatigue-crack-growth behavior under constant-amplitude cyclic conditions is influenced by maximum cyclic stress, S_{max}, and some measure of cyclic stress range, ΔS (such as stress ratio, R, or minimum cyclic stress, S_{min}), the instantaneous crack size, a, and other factors such as environment, frequency, and temperature. Thus, fatigue-crack-growth rate behavior can be characterized, in general form, by the relation

$$da/dN \approx \Delta a/\Delta N = g(S_{max}, \Delta S \text{ or } R \text{ or } S_{min}, a, \ldots). \qquad [1.4.13.3(a)]$$

By applying concepts of linear elastic fracture mechanics, the stress and crack size parameters can be combined into the stress-intensity factor parameter, K, such that Equation 1.4.13.3(a) may be simplified to

$$da/dN \approx \Delta a/\Delta N = g(K_{max}, \Delta K, \ldots) \qquad [1.4.13.3(b)]$$

where

K_{max} = the maximum cyclic stress-intensity factor
ΔK = $(1-R)K_{max}$, the range of the cyclic stress-intensity factor, for $R \geq 0$
ΔK = K_{max}, for $R \leq 0$.

At present, in the Handbook, the independent variable is considered to be simply ΔK and the data are considered to be parametric on the stress ratio, R, such that Equation 1.4.13.3(b) becomes

$$da/dN \approx \Delta a/\Delta N = g(\Delta K, R). \qquad [1.4.13.3(c)]$$

1.4.13.3 *Fatigue Crack Growth Data Presentation* — Fatigue crack growth rate data for constant amplitude cyclic loading conditions are presented as logarithmic plots of da/dN versus ΔK. Such information, such as that illustrated in Figure 1.4.13.3, are arranged by material alloy and heat treatment condition. Each curve represents a specific stress ratio, R, environment, and cyclic loading frequency. Specific details regarding test procedures and data interpolations are presented in Chapter 9.

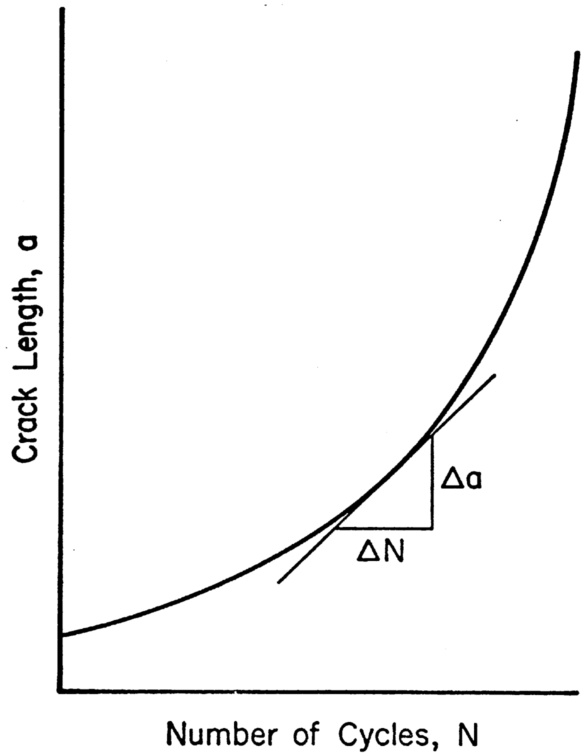

Figure 1.4.13.1(a). Fatigue crack-growth curve.

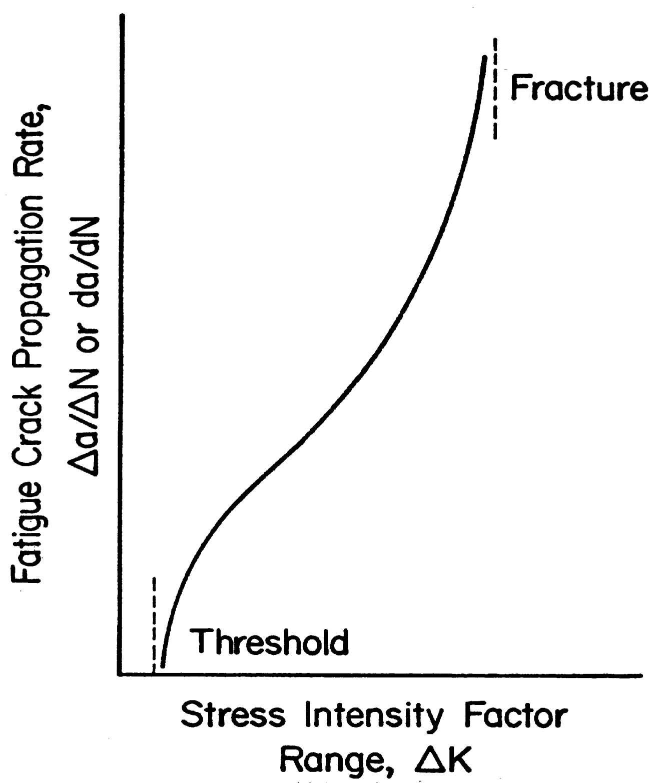

Figure 1.4.13.1(b). Fatigue crack-growth-rate curve.

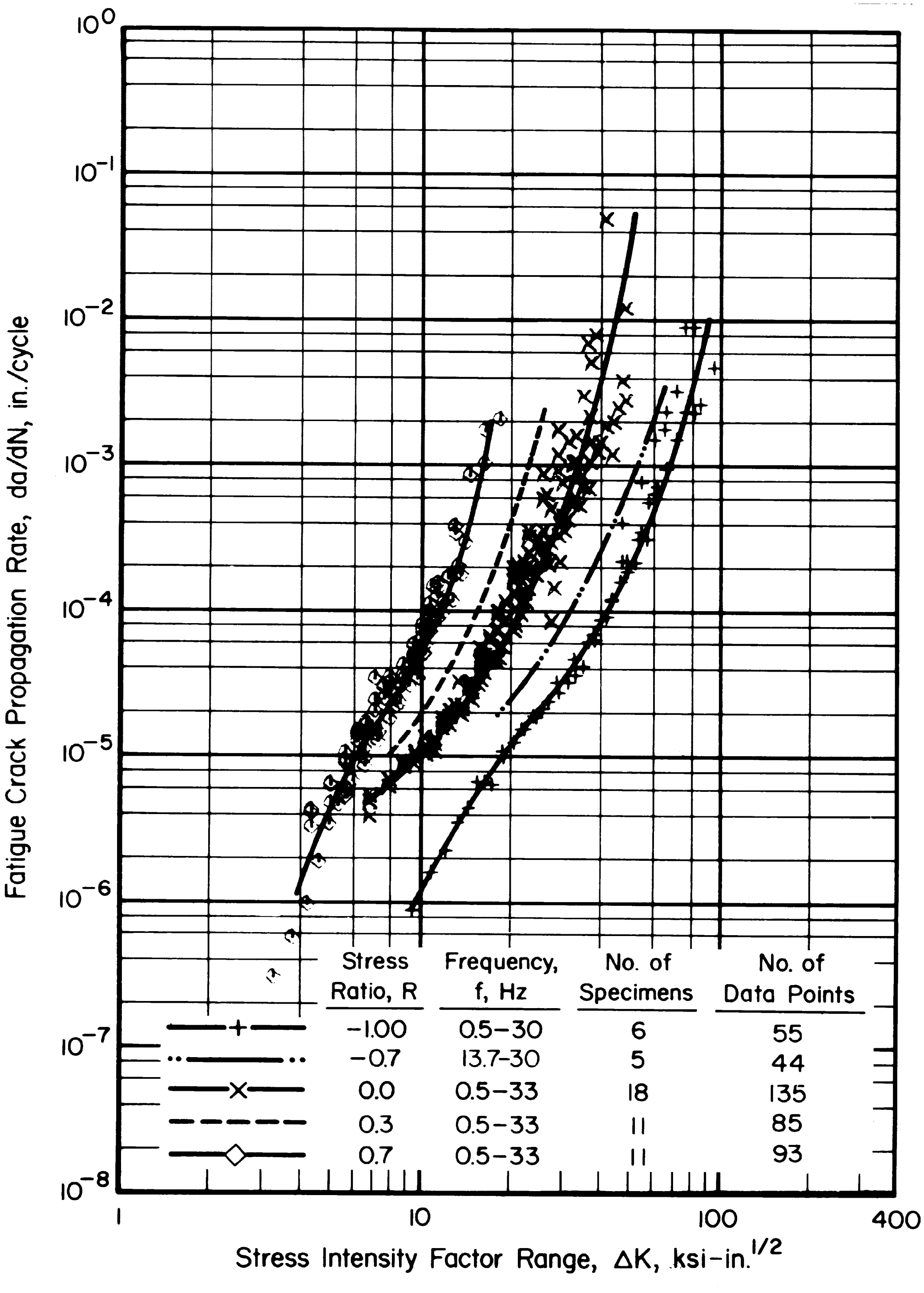

Figure 1.4.13.3. Sample display of fatigue crack growth rate data.

1.5 TYPES OF FAILURES

1.5.1 GENERAL — In the following discussion, failure will usually indicate fracture of a member or the condition of a member when it has attained maximum load.

1.5.2 MATERIAL FAILURES — Fracture can occur in either ductile or brittle fashions in the same material depending on the state of stress, rate of loading, and environment. The ductility of a material has a significant effect on the ability of a part to withstand loading and delay fracture. Although not a specific design property for ductile materials, some ductility data are provided in the Handbook to assist in material selections. The following paragraphs discuss the relationship between failure and the applied or induced stresses.

1.5.2.1 *Direct Tension or Compression* — This type of failure is associated with ultimate tensile or compressive stress of the material. For compression, it can only apply to members having large cross sectional dimensions relative to their lengths. See Section 1.4.5.1.

1.5.2.2 *Shear* — Pure shear failures are usually obtained when the shear load is transmitted over a very short length of a member. This condition is approached in the case of rivets and bolts. In cases where ultimate shear stress is relatively low, a pure shear failure can result. But, generally members subjected to shear loads fail under the action of the resulting normal stress, usually the compressive stress. See Equation 1.3.3.3. Failure of tubes in torsion are not caused by exceeding the shear ultimate stress, but by exceeding a normal compressive stress which causes the tube to buckle. It is customary to determine stresses for members subjected to shear in the form of shear stresses although they are actually indirect measures of the stresses actually causing failure.

1.5.2.3 *Bearing* — Failure of a material in bearing can consist of crushing, splitting, tearing, or progressive rapid yielding in the direction of load application. Failure of this type depends on the relative size and shape of the two connecting parts. The maximum bearing stress may not be applicable to cases in which one of the connecting members is relatively thin.

1.5.2.4 *Bending* — For sections not subject to geometric instability, a bending failure can be classed as either a tensile or compressive failure. Reference 1.5.2.4 provides methodology by which actual bending stresses above the material proportional limit can be used to establish maximum stress conditions. Actual bending stresses are related to the bending modulus of rupture. The bending modulus of rupture (f_b) is determined by Equation 1.3.2.3. When the computed bending modulus of rupture is found to be lower than the proportional limit strength, it represents an actual stress. Otherwise, it represents an apparent stress, and is not considered as an actual material strength. This is important when considering complex stress states, such as combined bending and compression or tension.

1.5.2.5 *Failure Due to Stress Concentrations* — Static stress properties represent pristine materials without notches, holes, or other stress concentrations. Such simplistic structural design is not always possible. Consideration should be given to the effect of stress concentrations. When available, references are cited for specific data in various chapters of the Handbook.

1.5.2.6 *Failure from Combined Stresses* — Under combined stress conditions, where failure is not due to buckling or instability, it is necessary to refer to some theory of failure. The "maximum shear" theory is widely accepted as a working basis in the case of isotropic ductile materials. It should be noted that this theory defines failure as the first yielding of a material. Any extension of this theory to cover conditions of final rupture must be based on evidence supported by the user. The failure of brittle materials under combined stresses is generally treated by the "maximum stress" theory. Section 1.4.11 contains a more complete discussion of biaxial behavior. References 1.5.2.6(a) through (c) offer additional information.

1.5.3 INSTABILITY FAILURES — Practically all structural members, such as beams and columns, particularly those made from thin material, are subject to failure due to instability. In general, instability can be classed as (1) primary or (2) local. For example, the failure of a tube loaded in compression can occur either through lateral deflection of the tube acting as a column (primary instability) or by collapse of the tube walls at stresses lower than those required to produce a general column failure. Similarly, an I-beam or other formed shape can fail by a general sidewise deflection of the compression flange, by local wrinkling of thin outstanding flanges, or by torsional instability. It is necessary to consider all types of potential failures unless it apparent that the critical load for one type is definitely the controlling condition.

Instability failures can occur in either the elastic range below the proportional limit or in the plastic range. These two conditions are distinguished by referring to either "elastic instability" or "plastic instability" failures. Neither type of failure is associated with a material's ultimate strength, but largely depends upon geometry.

A method for determining the local stability of aluminum alloy column sections is provided in Reference 1.7.1(b). Documents cited therein are the same as those listed in References 3.20.2.2(a) through (e).

1.5.3.1 *Instability Failures Under Compression* — Failures of this type are discussed in Section 1.6 (Columns).

1.5.3.2 *Instability Failures Under Bending* — Round tubes when subjected to bending are subject to plastic instability failures. In such cases, the failure criterion is the modulus of rupture. Equation 1.3.2.3, which was derived from theory and confirmed empirically with test data, is applicable. Elastic instability failures of thin walled tubes having high D/t ratios are treated in later sections.

1.5.3.3 *Instability Failures Under Torsion* — The remarks given in the preceding section apply in a similar manner to round tubes under torsional loading. In such cases, the modulus of rupture in torsion is derived through the use of Equation 1.3.2.6. See Reference 1.5.3.3.

1.5.3.4 *Failure Under Combined Loadings* — For combined loading conditions in which failure is caused by buckling or instability, no theory exists for general application. Due to the various design philosophies and analytical techniques used throughout the aerospace industry, methods for computing margin of safety are not within the scope of this Handbook.

1.6 COLUMNS

1.6.1 GENERAL — A theoretical treatment of columns can be found in standard texts on the strength of materials. Some of the problems which are not well defined by theory are discussed in this section. Actual strengths of columns of various materials are provided in subsequent chapters.

1.6.2 PRIMARY INSTABILITY FAILURES — A column can fail through primary instability by bending laterally (stable sections) or by twisting about some axis parallel to its own axis. This latter type of primary failure is particularly common to columns having unsymmetrical open sections. The twisting failure of a closed section column is precluded by its inherently high torsional rigidity. Since the amount of available information is limited, it is advisable to conduct tests on all columns subject to this type of failure.

1.6.2.1 *Columns with Stable Sections* — The Euler formula for columns which fail by lateral bending is given by Equation 1.3.8.2. A conservative approach in using this equation is to replace the elastic modulus (E) by the tangent modulus (E_t) given by Equation 1.3.8.1. Values for the restraint coefficient (c) depend on degrees of ends and lateral fixities. End fixities tend to modify the effective column length as indicated in Equation 1.3.8.1. For a pin-ended column having no end restraint, c = 1.0 and L′ = L. A fixity coefficient of c = 2 corresponds to an effective column length of L′ = 0.707 times the total length.

The tangent modulus equation takes into account plasticity of a material and is valid when the following conditions are met:

(a) The column adjusts itself to forcible shortening only by bending and not by twisting.
(b) No buckling of any portion of the cross section occurs.
(c) Loading is applied concentrically along the longitudinal axis of the column.
(d) The cross section of the column is constant along its entire length.

MIL-HDBK-5 provides typical stress versus tangent modulus diagrams for many materials, forms, and grain directions. These information are not intended for design purposes. Methodology is contained in Chapter 9 for the development of allowable tangent modulus curves.

1.6.2.2 ***Column Stress (f_{co})*** — The upper limit of column stress for primary failure is designated as f_{co}. By definition, this term should not exceed the compression ultimate strength, regardless of how the latter term is defined.

1.6.2.3 ***Other Considerations*** — Methods of analysis by which column failure stresses can be computed, accounting for fixities, torsional instability, load eccentricity, combined lateral loads, or varying column sections are contained in References 1.6.2.3(a) through (d).

1.6.3 LOCAL INSTABILITY FAILURES — Columns are subject to failure by local collapse of walls at stresses below the primary failure strength. The buckling analysis of a column subject to local instability requires consideration of the shape of the column cross section and can be quite complex. Local buckling, which can combine with primary buckling, leads to an instability failure commonly identified as crippling.

1.6.3.1 ***Crushing or Crippling Stress (f_{cc})*** — The upper limit of column stress for local failure is defined by either its crushing or crippling stress. The strengths of round tubes have been thoroughly investigated and considerable amounts of test results are available throughout literature. Fewer data are available for other cross sectional configurations and testing is suggested to establish specific information, e.g., the curve of transition from local to primary failure.

1.6.4 CORRECTION OF COLUMN TEST RESULTS — In the case of columns having unconventional cross sections which are subject to local instability, it is necessary to establish curves of transition from local to primary failure. In determining these column curves, sufficient tests should be made to cover the following points.

1.6.4.1 ***Nature of "Short Column Curve"*** — Test specimens should cover a range of L′/ρ values. When columns are to be attached eccentrically in structural application, tests should be designed to cover such conditions. This is important particularly in the case of open sections, as maximum load carrying capabilities are affected by locations of load and reaction points.

1.6.4.2 ***Local Failure*** — When local failure occurs, the crushing or crippling stress can be determined by extending the short column curve to a point corresponding to a zero value for L′/ρ. When a family of columns of the same general cross section is used, it is often possible to determine a relationship between crushing or crippling stress and some geometric factor. Examples are wall thickness, width, diameter, or some combination of these dimensions. Extrapolation of such data to conditions beyond test geometry extremes should be avoided.

1.6.4.3 ***Reduction of Column Test Results on Aluminum and Magnesium Alloys to Standard Material*** — The use of correction factors provided in Figures 1.6.4.3(a) through (i) is acceptable to the Air Force, the Navy, the Army, and the Federal Aviation Administration for use in reducing aluminum and magnesium alloys column test data into allowables. (Note that an alternate method is provided in Section 1.6.4.4). In using Figures 1.6.4.3(a) through (i), the correction of column test results to standard material is made by multiplying the stress obtained from testing a column specimen by the factor K. This factor may be considered applicable regardless of the type of failure involved, i.e., column crushing, crippling or twisting. Note that not all the information provided in these figures pertains to allowable stresses, as explained below.

The following terms are used in reducing column test results into allowable column stress:

F_{cy} is the design compression yield stress of the material in question, applicable to the gage, temper and grain direction along the longitudinal axis of a test column.

F_c' is the maximum test column stress achieved in test. Note that a letter (F) is used rather the customary lower case (f). This value can be an individual test result.

F_{cy}' is the compressive yield strength of the column material. Note that a letter (F) is used rather than the customary lower case (f). This value can be an individual test result using a standard compression test specimen.

Using the ratio of (F_c' / F_{cy}'), enter the appropriate diagram along the abscissa and extend a line upwards to the intersection of a curve with a value of (F_{cy}' / F_{cy}'). Linear interpolation between curves is permissible. At this location, extend a horizontal line to the ordinate and read the corresponding K-factor. This factor is then used as a multiplier on the measured column strength to obtain the allowable. The basis for this allowable is the same as that noted for the compression yield stress allowable obtained from the room temperature allowables table.

If the above method is not feasible, due to an inability of conducting a standard compression test of the column material, the compression yield stress of the column material may be estimated as follows: Conduct a standard tensile test of the column material and obtain its tensile yield stress. Multiply this value by the ratio of compression-to-tensile yield allowables for the standard material. This provides the estimated compression yield stress of the column material. Continue with the analysis as described above using the compression stress of a test column in the same manner.

If neither of the above methods are feasible, it may be assumed that the compressive yield stress allowable for the column is 15 percent greater than minimum established allowable longitudinal tensile yield stress for the material in question.

1.6.4.4 ***Reduction of Column Test Results to Standard Material--Alternate Method*** — For materials that are not covered by Figures 1.6.4.4(a) through (i), the following method is acceptable for all materials to the Air Force, the Navy, the Army, and the Federal Aviation Administration.

(1) Obtain the column material compression properties: F_{cy}, E_c, n_c.

(2) Determine the test material column stress (f_c') from one or more column tests.

(3) Determine the test material compression yield stress (f_{cy}') from one or more tests.

(4) Assume E_c and n_c from (1) apply directly to the column material. They should be the same material.

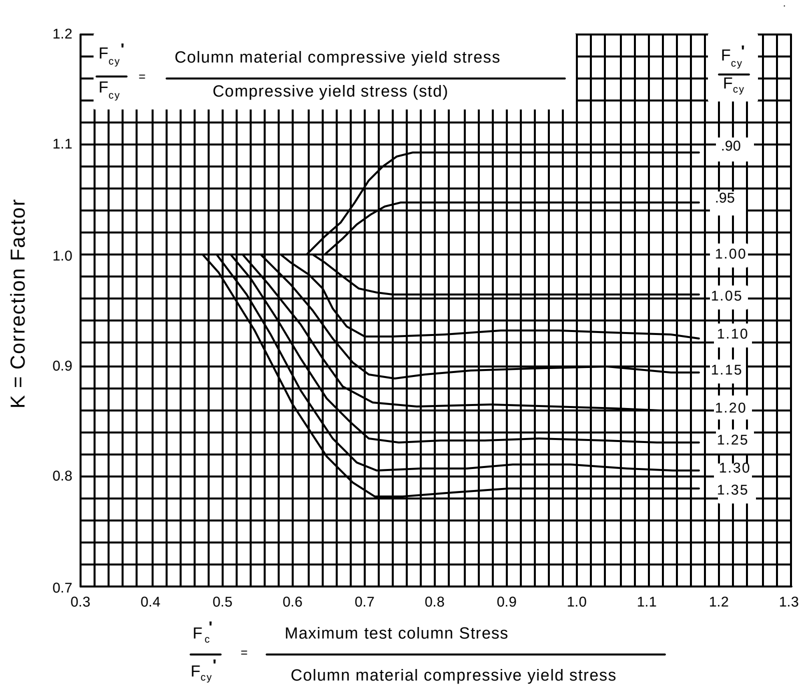

Figure 1.6.4.4(a). Nondimensional material correction chart for 2024-T3 sheet.

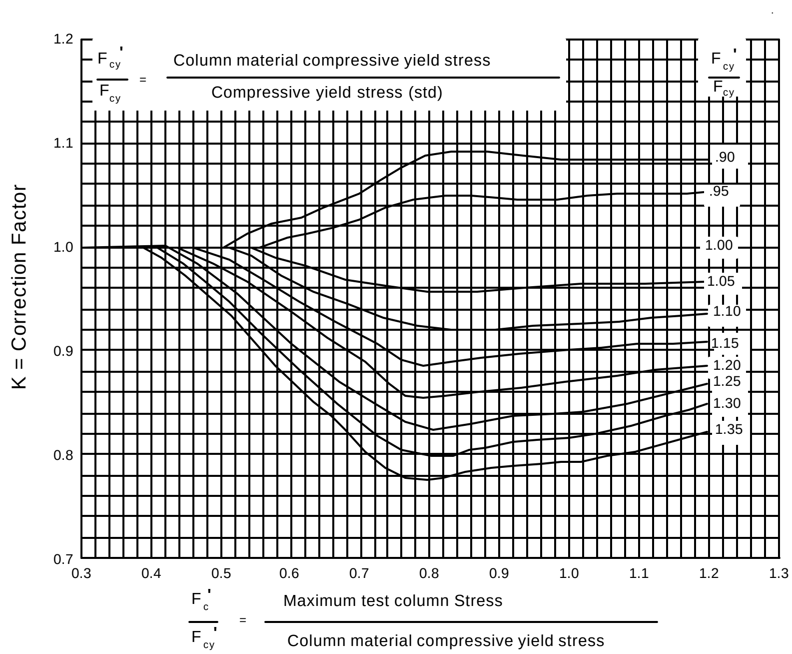

Figure 1.6.4.4(b). Nondimensional material correction chart for 2024-T3 clad sheet.

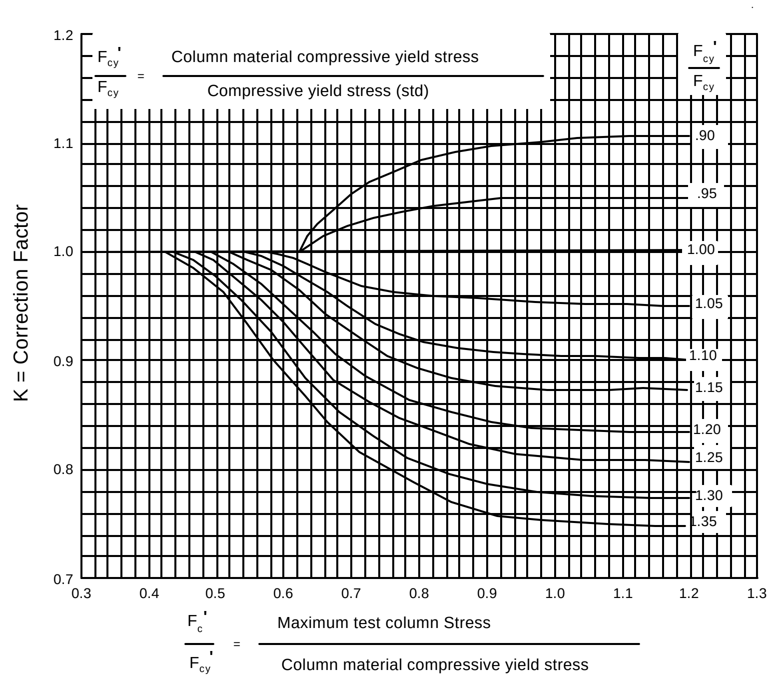

Figure 1.6.4.4(c). Nondimensional material correction chart for 2024-T4 extrusion less than 1/4 inch thick.

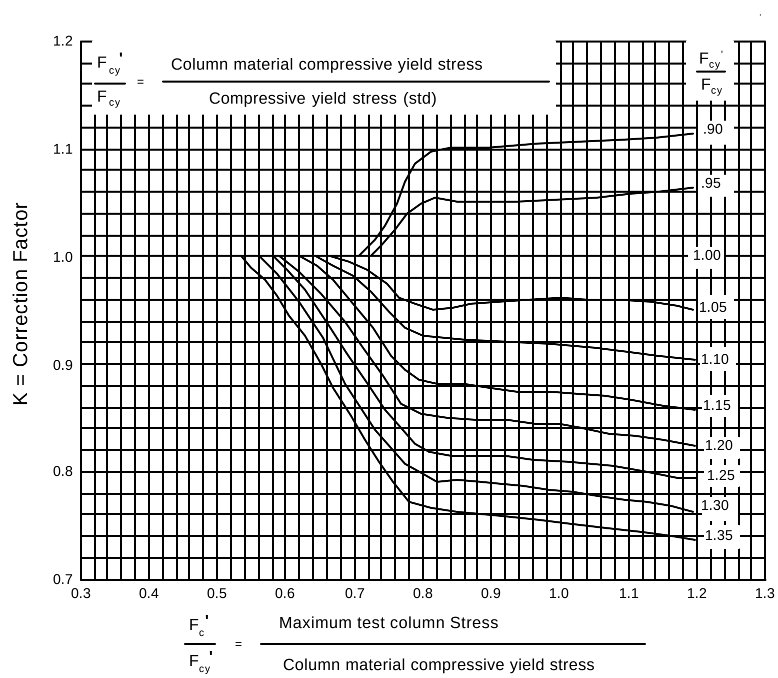

Figure 1.6.4.4(d). Nondimensional material correction chart for 2024-T4 extrusion 1/4 to 1-1/2 inches thick.

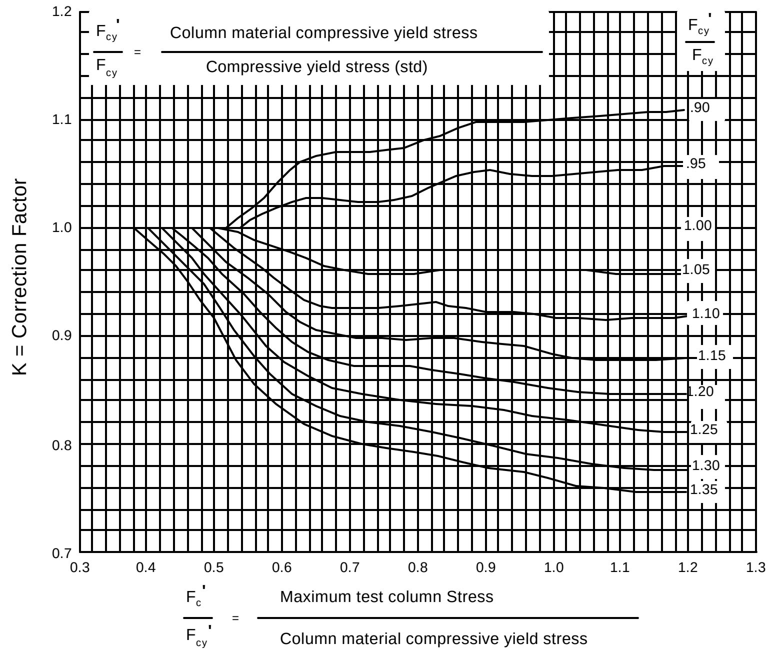

Figure 1.6.4.4(e). Nondimensional material correction chart for 2024-T3 tubing.

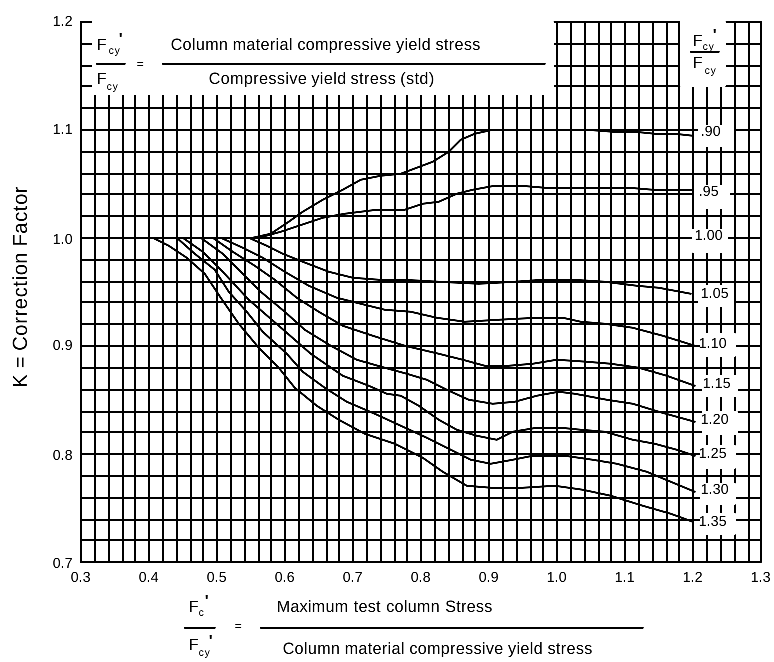

Figure 1.6.4.4(f). Nondimensional material correction chart for clad 2024-T3 sheet.

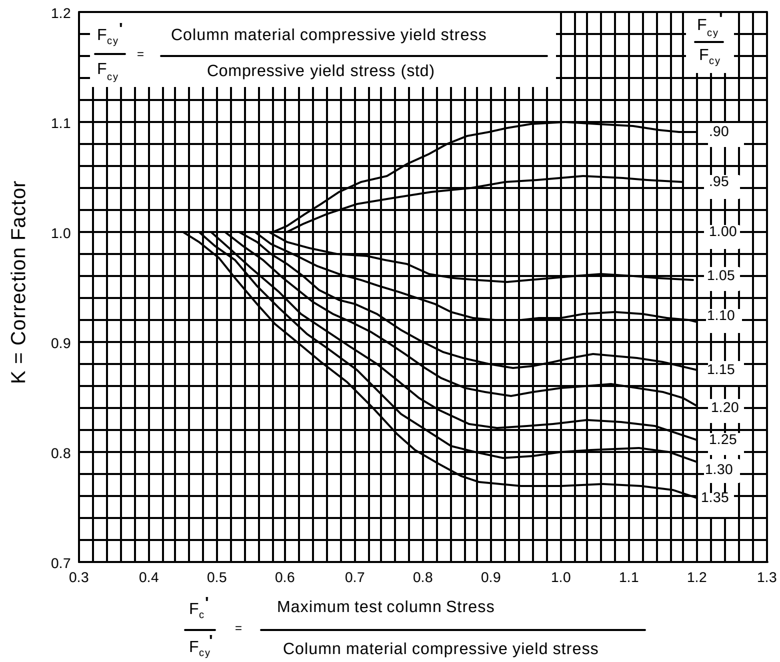

Figure 1.6.4.4(g). Nondimensional material correction chart for 7075-T6 sheet.

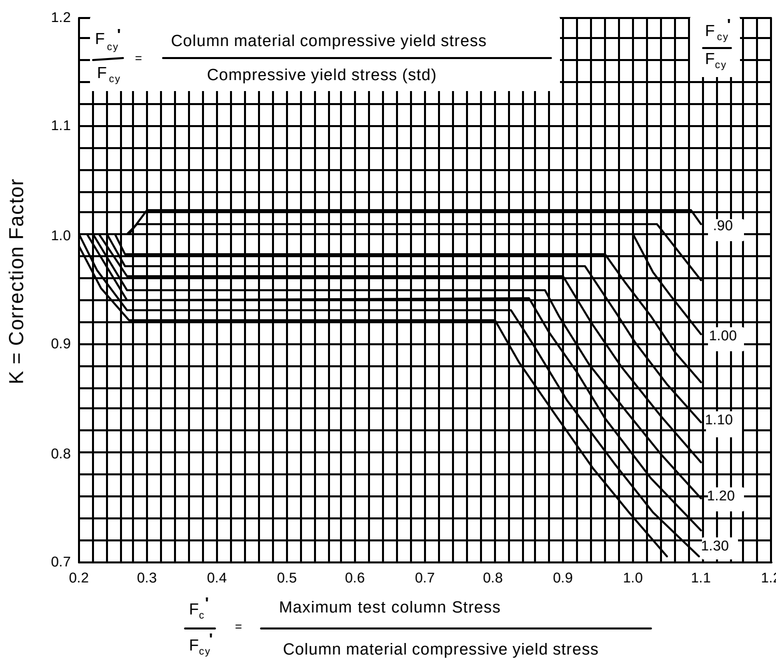

Figure 1.6.4.4(h). Nondimensional material correction chart for AZ31B-F and AZ61A-F extrusion.

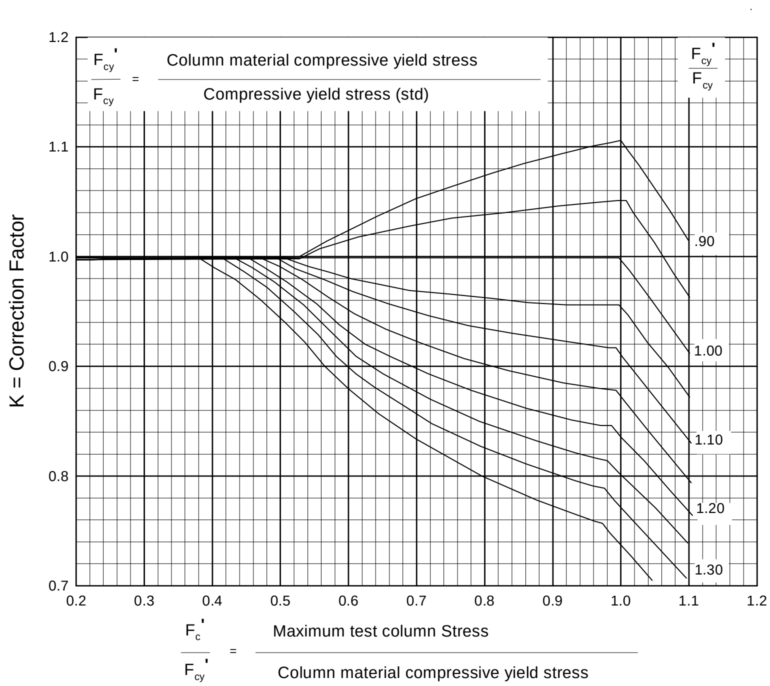

Figure 1.6.4.4(i). Nondimensional material correction chart for AZ31B-H24 sheet.

(5) Assume that geometry of the test column is the same as that intended for design. This means that a critical slenderness ratio value of (L'/ρ) applies to both cases.

(6) Using the conservative form of the basic column formula provided in Equation 1.3.8.1, this enables an equality to be written between column test properties and allowables. If

$$(L'/\rho)\text{ for design} = (L'/\rho)\text{ of the column test} \qquad [1.6.4.4(a)]$$

Then

$$(F_c/E_t)\text{ for design} = (f_c'/E_t')\text{ from test} \qquad [1.6.4.4(b)]$$

(7) Tangent modulus is defined as:

$$E_t = df / de \qquad [1.6.4.4(c)]$$

(8) Total strain (e) is defined as the sum of elastic and plastic strains, and throughout the Handbook is used as:

$$e = e_E + e_p \qquad [1.6.4.4(d)]$$

or,

$$e = \frac{f}{E} + 0.002\left(\frac{f}{f_y}\right)^n \qquad [1.6.4.4(e)]$$

So, Equation 1.6.4.4(c) can be rewritten as follows:

$$E_t = \frac{f}{\dfrac{f}{E} + 0.002n\left(\dfrac{f}{f_y}\right)^n} \qquad [1.6.4.4(f)]$$

Tangent modulus, for the material in question, using its compression allowables is:

$$E_t = \frac{F_c}{\dfrac{F_c}{E_c} + 0.002n_c\left(\dfrac{F_c}{F_{cy}}\right)^{n_c}} \qquad [1.6.4.4(g)]$$

In like manner, tangent modulus for the same material with the desired column configuration is:

$$E_t' = \frac{f_c'}{\dfrac{f_c'}{E_c} + 0.002n_c\left(\dfrac{f_c'}{f_{cy}'}\right)^{n_c}} \qquad [1.6.4.4(h)]$$

Substitution of Equations 1.6.4.4(g) and 1.6.4.4(h) for their respective terms in Equation 1.6.4.4(b) and simplifying provides the following relationship:

$$\frac{F_c}{E_c} + 0.002n_c\left(\frac{F_c}{F_{cy}}\right)^{n_c} = \frac{f_c'}{E_c} + 0.002n_c\left(\frac{f_c'}{f_{cy}'}\right)^{n_c} \qquad [1.6.4.4(i)]$$

The only unknown in the above equation is the term F_c , the allowable column compression stress. This property can be solved by an iterative process.

This method is also applicable at other than room temperature, having made adjustments for the effect of temperature on each of the properties. It is critical that the test material be the same in all respects as that for which allowables are selected from the Handbook. Otherwise, the assumption made in Equation 1.6.4.4(c) above is not valid. Equation 1.6.4.4(i) must account for such differences in moduli and shape factors when applicable.

1.7 THIN-WALLED AND STIFFENED THIN-WALLED SECTIONS

A bibliography of information on thin-walled and stiffened thin-walled sections is contained in References 1.7(a) and (b).

REFERENCES

1.4.3.1 Goodman, S. and Russell, S.B., U.S. Air Force, "Poisson's Ratio of Aircraft Sheet Materials for Large Strain," WADC-TR-53-7, 58 pp (June1953).

1.4.4 "Test Methods of Tension Testing of Metallic Materials," ASTM E 8.

1.4.5(a) Hyler, W.S., "An Evaluation of Compression-Testing Techniques for Determining Elevated Temperature Properties of Titanium Sheet," Titanium Metallurgical Laboratory Report No. 43, Battelle Memorial Institute, 38 pp, Appendix 28 pp (June 8, 1956).

1.4.5(b) "Compression Testing of Metallic Materials at Room Temperature," ASTM E 9.

1.4.6 Stange, A.H., Ramberg, W. and Back, G., "Torsion Tests of Tubes," National Advisory Committee for Aeronautics, Report No. 601, pp 515-535 (Feb. 1937).

1.4.7(a) Stickley, G.W. and Moore, A.A., "Effects of Lubrication and Pin Surface on Bearing Strengths of Aluminum and Magnesium Alloys," Materials Research and Standards, **2**, (9), pp 747-751 (September 1962).

1.4.7(b) "Method of Pin-Type Bearing Test of Metallic Materials," ASTM E 238.

1.4.8.2.1(a) "Recommended Practice for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials," ASTM E 139.

1.4.8.2.1(b) Rice, Richard, "Reference Document for the Analysis of Creep and Stress Rupture Data in MIL-HDBK-5," AFWAL-TR-81-4097 (September 1981).

1.4.8.2.1(c) Aarnes, M.N. and Tuttle, M.M., "Presentation of Creep Data for Design Purposes," ASD Technical Report 61-216 (June 1961) (MCIC 45114).

1.4.9(a) "Recommended Practice for Constant Amplitude Axial Fatigue Tests of Metallic Materials," ASTM E 466.

1.4.9(b) "Recommended Practice for Constant-Amplitude Low-Cycle Fatigue Testing," ASTM E 606.

1.4.9.2(a) Grover, H.J., "Fatigue of Aircraft Structures," Prepared for Naval Air Systems Command, Department of the Navy, 335 pp (1966).

1.4.9.2(b) Osgood, C.C., "Fatigue Design," Wiley-Interscience, A Division of John Wiley and Sons, Inc., 523 pp (1970).

1.4.11 Bert, C.W., Mills, E.J. and Hyler, W.S., "Mechanical Properties of Aerospace Structural Alloys Under Biaxial-Stress Conditions," AFML-TR-66-229, (August 1966).

1.4.12.2(a) "Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials," ASTM E 399.

1.4.13.1 "Test Method for Measurements of Fatigue Crack Growth Rates," ASTM E 647.

1.4.13.2 Paris, P.C., “The Fracture Mechanics Approach to Fatigue,” Proc. 10th Sagamore Conference, p. 107, Syracuse University Press (1965).

1.5.2.4 Cozzone, F.P., “Bending Strength in the Plastic Range,” Journal of the Aeronautical Sciences, **10**, pp 137-151, (1943).

1.5.2.6(a) Dieter, G.E., Jr., “Mechanical Metallurgy,” McGraw-Hill Book Company, Inc., 615 pp (1961).

1.5.2.6(b) Freudenthal, A.M., “The Inelastic Behavior of Engineering Materials and Structures,” John Wiley and Sons, Inc., New York, 587 pp (1950).

1.5.2.6(c) Parker, E.R., “Brittle Behavior of Engineering Structures,” John Wiley and Sons, Inc., New York, 323 pp (1957).

1.5.3.3 Lundquist, E.E., “Strength Tests of Thin-Walled Duralumin Cylinders in Pure Bending,” U.S. National Advisory Committee for Aeronautics, Technical Note No. 479, 17 pp (December 1933).

1.6.2.3(a) Hill, H.N. and Clark, J.W., “Straight-Line Column Formulas for Aluminum Alloys,” Aluminum Company of America, Aluminum Research Laboratories, Technical Paper No. 12, 8 pp (1955).

1.6.2.3(b) AFFDL-TR-69-42, “Stress Analysis Manual,” Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base (February 1970).

1.6.2.3(c) “Astronautic Structure Manual,” George C. Marshall Space Flight Center (August 15, 1970).

1.6.2.3(d) Niles, A.S., and Newell, J.S., “Airplane Structure,” 2, Third Edition, John Wiley and Sons (1943).

1.7(a) “Index of Aircraft Structures Research Reports,” U.S. National Advisory Committee for Aeronautics, Index No. 7E29, 40 pp (June 1947).

1.7(b) Gerard, and Becker, H., “Handbook of Structural Stability,” National Advisory Committee for Aeronautics Technical Note, Nos. 3781, 102 pp (July 1957); 3782, 72 pp (July 1957); 3783, 154 pp (August 1957); 3784, 93 pp (August 1957); and 3785, 89 pp (August 1957).

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2.2.0.3 *Environmental Considerations* — Carbon steels have poor oxidation resistance above about 900 to 1000°F. Strength and oxidation-resistance criteria generally preclude the use of carbon steels above 900°F.

Carbon steels may undergo an abrupt transition from ductile to brittle behavior. This transition temperature varies widely for different carbon steels depending on many factors. Cautions should be exercised in the application of carbon steels to assure that the transition temperature of the selected alloy is below the service temperature. Additional information is contained in References 2.2.0.3(a) and (b).

The corrosion resistance of carbon steels is relatively poor; clean surfaces rust rapidly in moist atmospheres. Simple oil film protection is adequate for normal handling. For aerospace applications, the carbon steels are usually plated to provide adequate corrosion protection.

2.2.1 AISI 1025

2.2.1.0 *Comments and Properties* — AISI 1025 is an excellent general purpose steel for the majority of shop requirements, including jigs, fixtures, prototype mockups, low torque shafting, and other applications. It is not generally classed as an airframe structural steel. However, it is available in aircraft quality as well as commercial quality.

Manufacturing Considerations — Cold-finished flat-rolled products are supplied principally where maximum strength, good surface finish, or close tolerance is desirable. Reasonably good forming properties are found in AISI 1025. The machinability of bar stock is rated next to these sulfurized types of free-machining steels, but the resulting surface finish is poorer.

Specifications and Properties — Material specifications for AISI 1025 steel are presented in Table 2.2.1.0(a). The room-temperature mechanical and physical properties are shown in Table 2.2.1.0(b). The effect of temperature on thermal expansion is shown in Figure 2.2.1.0.

Table 2.2.1.0(a). Material Specifications for AISI 1025 Carbon Steel

Specification	Form
ASTM A 108	Bar
AMS 5075	Seamless tubing
AMS-T-5066[a]	Tubing
AMS 5077	Tubing
AMS 5046	Sheet, strip, and plate
AMS-S-7952	Sheet and strip

a Noncurrent specification

Table 2.2.1.0(b). Design Mechanical and Physical Properties of AISI 1025 Carbon Steel

Specification	AMS 5046 and MIL-S-7952	AMS 5075, AMS 5077 and AMS-T-5066[a]	ASTM A 108
Form	Sheet, strip, and plate	Tubing	Bar
Condition	Annealed	Normalized	All
Thickness, in.	...	...	...
Basis	S	S	S[b]
Mechanical Properties:			
F_{tu}, ksi:			
L	55	55	55
LT	55	55	55
ST	...	...	55
F_{ty}, ksi:			
L	36	36	36
LT	36	36	36
ST	...	...	36
F_{cy}, ksi:			
L	36	36	36
LT	36	36	36
ST	...	...	36
F_{su}, ksi	35	35	35
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	90	90	90
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
e, percent:			
L	...	c	c
LT	c	...	...
E, 10^3 ksi		29.0	
E_c, 10^3 ksi		29.0	
G, 10^3 ksi		11.0	
μ		0.32	
Physical Properties:			
ù , lb/in.^{3}		0.284	
C, Btu/(lb)(EF)		0.116 (122 to 212EF)	
K, Btu/[(hr)(ft^2)(EF)/ft]		30.0 (at 32EF)	
á, 10^{-6} in./in./EF		See Figure 2.2.1.0	

a Noncurrent specification.

2.3.1 SPECIFIC ALLOYS

2.3.1.0 *Comments and Properties* — AISI 4130 is a chromium-molybdenum steel that is in general use due to its well-established heat-treating practices and processing techniques. It is available in all sizes of sheet, plate, and tubing. Bar stock of this material is also used for small forgings under one-half inch in thickness. AISI 4135, a slightly higher carbon version of AISI 4130, is available in sheet, plate, and tubing.

AISI 4140 is a chromium-molybdenum steel that can be heat treated in thicker sections and to higher strength levels than AISI 4130. This steel is generally used for structural machined and forged parts one-half inch and over in thickness. It can be welded but it is more difficult to weld than the lower carbon grade AISI 4130.

AISI 4340 is a nickel-chromium-molybdenum steel that can be heat treated in thicker sections and to higher strength levels than AISI 4140.

AISI 8630, 8735, and 8740 are nickel-chromium-molybdenum steels that are considered alternates to AISI 4130, 4135, and 4140, respectively.

There are a number of steels available with compositions that represent modifications to the AISI grades described above. Four of the steels that have been used rather extensively at F_{tu} = 220 ksi are D6AC, Hy-Tuf, 4330V, and 4335V. It should be noted that this strength level is not used for AISI 4340 due to embrittlement encountered during tempering in the range of 500 to 700°F. In addition, AISI 4340 and 300M are utilized at strength levels of F_{tu} = 260 ksi or higher. The alloys, AISI 4340, D6AC, 4330V, 4335V, and 300M, are available in the consumable electrode melted grade. Material specifications for these steels are presented in Tables 2.3.1.0(a) and (b).

The room-temperature mechanical and physical properties for these steels are presented in Tables 2.3.1.0(c) through 2.3.1.0(g). Mechanical properties for heat-treated materials are valid only for steel heat treated to produce a quenched structure containing 90 percent or more martensite at the center. Figure 2.3.1.0 contains elevated temperature curves for the physical properties of AISI 4130 and AISI 4340 steels.

2.3.1.1 *AISI Low-Alloy Steels* — Elevated temperature curves for heat-treated AISI low-alloy steels are presented in Figures 2.3.1.1.1 through 2.3.1.1.4. These curves are considered valid for each of these steels in each heat-treated condition but only up to the maximum temperatures listed in Table 2.3.0.1(b).

2.3.1.2 *AISI 4130 and 8630 Steels* — Typical stress-strain and tangent-modulus curves for AISI 8630 are shown in Figures 2.3.1.2.6(a) through (c). Best-fit S/N curves for AISI 4130 steel are presented in Figures 2.3.1.2.8(a) through (h).

2.3.1.3 *AISI 4340 Steel* — Typical stress-strain and tangent-modulus curves for AISI 4340 are shown in Figures 2.3.1.3.6(a) through (c). Typical biaxial stress-strain curves and yield-stress envelopes for AISI 4340 alloy steel are presented in Figures 2.3.1.3.6(d) through (g). Best-fit S/N curves for AISI 4340 are presented in Figures 2.3.1.3.8(a) through (o).

2.3.1.4 *300M Steel* — Best-fit S/N curves for 300M steel are presented in Figures 2.3.1.4.8(a) through (d). Fatigue-crack-propagation data for 300M are shown in Figure 2.3.1.4.9.

2.3.1.5 *D6AC Steel* — Fatigue-crack-propagation data for D6AC steel are presented in Figure 2.3.1.5.9.

Table 2.3.1.0(a). Material Specifications for Air Melted Low-Alloy Steels

Alloy	Form		
	Sheet, strip, and plate	Bars and forgings	Tubing
4130	AMS-S-18729, AMS 6350[a], AMS 6351[a]	AMS-S-6758[a], AMS 6348[a], AMS 6370[a], AMS 6528[a]	AMS-T-6736, AMS 6371[a], AMS 6360, AMS 6361, AMS 6362, AMS 6373, AMS 6374
8630	AMS-S-18728, AMS 6355[a]	AMS-S-6050, AMS 6280[a]	AMS 6281[a]
4135	AMS 6352[a]	...	AMS 6372[a], AMS 6365, AMS-T-6735[b]
8735	AMS 6357[a]	AMS 6320[a]	AMS 6282[a]
4140	AMS 6395[a]	AMS-S-5626[a], AMS 6382[a], AMS 6349[a], AMS 6529[a]	AMS 6381[a]
4340	AMS 6359[a]	AMS-S-5000[a], AMS 6415[a]	AMS 6415[a]
8740	AMS 6358[a]	AMS-S-6049[b], AMS 6327, AMS 6322[a]	AMS 6323[a]
4330V	...	AMS 6427[a]	AMS 6427[a]
4335V	AMS 6433	AMS 6430	AMS 6430

a Specification does not contain minimum mechanical properties.
b Noncurrent specification.

Table 2.3.1.0(b). Material Specifications for Consumable Electrode Melted Low-Alloy Steels

Alloy	Form		
	Sheet, strip, and plate	Bar and forgings	Tubing
4340	AMS 6454[a]	AMS 6414	AMS 6414
D6AC	AMS 6439	AMS 6431, AMS 6439	AMS 6431
4330V	...	AMS 6411	AMS 6411
Hy-Tuf	...	AMS 6425	AMS 6425
4335V	AMS 6435	AMS 6429	AMS 6429
300M (0.40C)	...	AMS 6417	AMS 6417
300M (0.42C)	...	AMS 6419, AMS 6257	AMS 6419, AMS 6257

a Specification does not contain minimum mechanical properties.

Table 2.3.1.0(c_1). Design Mechanical and Physical Properties of Air Melted Low-Alloy Steels

Alloy	AISI 4130		AISI 4135		AISI 8630	
Specification [see Tables 2.3.1.0(a) and (b)]	AMS 6360 AMS 6373 AMS 6374 AMS-T-6736 AMS-S-18729		AMS 6365 AMS-T-6735[a]		AMS-S-18728	
Form	Sheet, strip, plate, and tubing		Tubing		Sheet, strip, and plate	
Condition	Normalized and tempered, stress relieved[b]					
Thickness or diameter, in.	#0.188	>0.188	#0.188	#0.188	#0.188	#0.188
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi	95	90	100	95	95	90
F_{ty}, ksi	75	70	85	80	75	70
F_{cy}, ksi	75	70	89	84	75	70
F_{su}, ksi	57	54	60	57	57	54
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	200	190	190	180	200	190
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	129	120	146	137	129	120
e, percent	See Table 2.3.1.0(d)					
E, 10^3 ksi	29.0					
E_c, 10^3 ksi	29.0					
G, 10^3 ksi	11.0					
μ	0.32					
Physical Properties:						
ù , lb/in.^{3}	0.283					
C, K, and á	See Figure 2.3.1.0					

a Noncurrent specification.
b Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

Table 2.3.1.0(c_2). Design Mechanical and Physical Properties of Air Melted Low-Alloy Steels

Alloy	AISI 4130		
Specification [see Tables 2.3.1.0(a) and (b)]	AMS 6361 AMS-T-6736	AMS 6362 AMS-T-6736	AMS-T-6736
Form	Tubing		
Condition	Quenched and tempered[a]		
Thickness or diameter, in.	#0.188	#0.188	All Walls
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi	125	150	180
F_{ty}, ksi	100	135	165
F_{cy}, ksi	109	141	173
F_{su}, ksi	75	90	108
F_{bru}, ksi:			
(e/D = 1.5)	194	231	277
(e/D = 2.0)	251	285	342
F_{bry}, ksi:			
(e/D = 1.5)	146	210	257
(e/D = 2.0)	175	232	284
e, percent	See Table 2.3.1.0(e)		
E, 10^3 ksi	29.0		
E_c, 10^3 ksi	29.0		
G, 10^3 ksi	11.0		
μ	0.32		
Physical Properties:			
ù , lb/in.^{3}	0.283		
C, K, and *á*	See Figure 2.3.1.0		

a Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

Table 2.3.1.0(c₃). Design Mechanical and Physical Properties of Air Melted Low-Alloy Steels

Alloy	AISI 8630	AISI 8740	
Specification [see Tables 2.3.1.0(a) and (b)]	AMS-S-6050	AMS-S-6049[a]	AMS 6327
Form	Bars and forgings		
Condition	Quenched and tempered[b]		
Thickness or diameter, in.	#1.500	#1.750	
Basis	S	S	
Mechanical Properties:			
F_{tu}, ksi	125	125	125
F_{ty}, ksi	100	103	100
F_{cy}, ksi	109	108	109
F_{su}, ksi	75	75	75
F_{bru}, ksi:			
(e/D = 1.5)	194	192	194
(e/D = 2.0)	251	237	251
F_{bry}, ksi:			
(e/D = 1.5)	146	160	146
(e/D = 2.0)	175	177	175
e, percent	See Table 2.3.1.0(e)		
E, 10^3 ksi	29.0		
E_c, 10^3 ksi	29.0		
G, 10^3 ksi	11.0		
μ	0.32		
Physical Properties:			
ù , lb/in.³	0.283		
C, *K*, and á	See Figure 2.3.1.0		

a Noncurrent specification
b Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

Table 2.3.1.0 (C_4). Design Mechanical and Physical properties of Air Melted Low-Alloy Steels

Alloy	AISI 4135			
Specification [see Tables 2.3.1.0(a) and (b)]	MIL-T-6753			
Form	Tubing			
Condition	Quenched and tempered[a]			
Wall thickness, in	≤0.8			<0.5[b]
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi	125	150	180	200
F_{ty}, ksi	100	135	165	165
F_{cy}, ksi .	109	141	173	181
F_{su}, ksi .	75	90	108	120
F_{bru}, ksi:				
(e/D = 1.5)	194	231	277	308
(e/D = 2.0)	251	285	342	380
F_{bry}, ksi:				
(e/D = 1.5)	146	210	257	274
(e/D = 2.0)	175	232	284	302
e, percent	See Table 2.3.1.0(e)			
E, 10^3 ksi	29.0			
E_c, 10^3 ksi	29.0			
G, 10^3 ksi	11.0			
μ	0.32			
Physical Properties:				
ω, lb/in.^{3}	0.283			
C, K, and α	See Figure 2.3.1.0			

a Design values are applicable only to parts for which the indicated F_{tu} and through hardening has been substantiated by adequate quality control testing.

b Wall thickness at which through hardening is achieved and verified through quality control testing.

Table 2.3.1.0(d). Minimum Elongation Values for Low-Alloy Steels in Condition N

Form	Thickness, in.	Elongation, percent	
		Full tube	Strip
Sheet, strip, and plate (T)	Less than 0.062	--	8
	Over 0.062 to 0.125 incl.	--	10
	Over 0.125 to 0.187 incl.	--	12
	Over 0.187 to 0.249 incl.	--	15
	Over 0.249 to 0.749 incl.	--	16
	Over 0.749 to 1.500 incl.	--	18
Tubing (L)	Up to 0.035 incl. (wall)	10	5
	Over 0.035 to 0.188 incl.	12	7
	Over 0.188	15	10

Table 2.3.1.0(e). Minimum Elongation Values for Heat-Treated Low-Alloy Steels

F_{tu}, ksi	Round specimens (L)		Elongation in 2 in., percent				
			Sheet specimens			Tubing (L)	
	Elongation in 4D, percent	Reduction of area, percent	Less than 0.032 in. thick	0.032 to 0.060 in. thick	Over 0.060 in. thick	Full tube	Strip
125	17	55	5	7	10	12	7
140	15	53	4	6	9	10	6
150	14	52	4	6	9	10	6
160	13	50	3	5	8	9	6
180	12	47	3	5	7	8	5
200	10	43	3	4	6	6	5

Table 2.3.1.0(f_1). Design Mechanical and Physical Properties of Low-Alloy Steels

Alloy	Hy-Tuf	4330V	4335V	4335V	D6AC	AISI 4340[a]	0.40C 300M	0.42C 300M
Specification	AMS 6425	AMS 6411	AMS 6430	AMS 6429	AMS 6431	AMS 6414	AMS 6417	AMS 6257 AMS 6419
Form	Bar, forging, tubing							
Condition	Quenched and tempered[b]							
Thickness or diameter, in.	c				d	e	f	
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi	220	220	205	240	220	260	270	280
F_{ty}, ksi	185	185	190	210	190	217	220	230
F_{cy}, ksi	193	193	199	220	198	235	236	247
F_{su}, ksi	132	132	123	144	132	156	162	168
F_{bru}, ksi:								
(e/D = 1.5)	297	297	315	369	297	347	414[g]	430[g]
(e/D = 2.0)	385	385	389	465	385	440	506[g]	525[g]
F_{bry}, ksi:								
(e/D = 1.5)	267	267	296	327	274	312	344[c]	360[c]
(e/D = 2.0)	294	294	327	361	302	346	379[c]	396[c]
e, percent:								
L	10	10	10	10	12	10	8	7
LT	5[a]	5[a]	7	7	9	...	...	...
E, 10^3 ksi	29.0							
E_c, 10^3 ksi	29.0							
G, 10^3 ksi	11.0							
μ	0.32							
Physical Properties:								
ù , lb/in.^{3}	0.283							
C, *K*, and *á*	See Figure 2.3.1.0							

a Applicable to consumable-electrode vacuum-melted material only.
b Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.
c Thickness# 1.70 in. for quenching in molten salt at desired tempering temperature (martempering); #2.50 in. for quenching in oil at flow rate of 200 feet/min.
d Thickness# 3.50 in. for quenching in molten salt at desired tempering temperature (martempering); #5.00 in. for quenching in oil at flow rate of 200 feet/min.
e Thickness# 1.70 in. for quenching in molten salt at desired tempering temperature (martempering); #2.50 in. for quenching in oil at flow rate of 200 feet/min.; #3.50 in. for quenching in water at a flow rate of 200 feet/min.
f Thickness #5.00 in. for quenching in oil at a flow rate of 200 feet/min.
g Bearing values are "dry pin" values per Section 1.4.7.1.

Table 2.3.1.0(f_2). Design Mechanical and Physical Properties of Low-Alloy Steels

Alloy	4335V	D6AC	
Specification	AMS 6435	AMS 6439	
Form	Sheet, strip, and plate		
Condition	Quenched and tempered[a]		
Thickness or diameter, in.	b	#0.250	$0.251
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi	220	215	224
F_{ty}, ksi	190	190	195
F_{cy}, ksi	198	198	203
F_{su}, ksi	132	129	134
F_{bru}, ksi:[c]			
(e/D = 1.5)	297	290	302
(e/D = 2.0)	385	376	392
F_{bry}, ksi:[c]			
(e/D = 1.5)	274	274	281
(e/D = 2.0)	302	302	310
e, percent:			
L	10	...	...
LT	7	7	7
E, 10^3 ksi	29.0		
E_c, 10^3 ksi	29.0		
G, 10^3 ksi	11.0		
μ	0.32		
Physical Properties:			
ù, lb/in.^{3}	0.283		
C, K, and á	See Figure 2.3.1.0		

a Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

b Thickness #1.70 in. for quenching in molten salt at desired tempering temperature (martempering); #2.50 in. for quenching in oil at a flow rate of 200 feet/min.

c Bearing values are “dry pin” values per Section 1.4.7.1.

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Table 2.3.1.0(h$_1$). Design Mechanical and Physical Properties of Low-Alloy Steels

Alloy	AISI 4130		AISI 4135		AISI 8630		AISI 8735	
Specification [see Tables 2.3.1.0(a) and (b)]	AMS 6350 AMS 6528 AMS-S-6758		AMS 6352 AMS 6372		AMS 6281		AMS 6357	
Form	Sheet, strip, plate, bars, and forgings		Sheet, strip, plate, and tubing		Tubing		Sheet, strip, and plate	
Condition	Normalized and tempered, stress relieved[a]							
Thickness or diameter, in.	#0.188	>0.188	#0.188	>0.188	#0.188	>0.188	#0.188	>0.188
Basis	b							
Mechanical Properties:								
F_{tu}, ksi	95	90	95	90	95	90	95	90
F_{ty}, ksi	75	70	75	70	75	70	75	70
F_{cy}, ksi	75	70	75	70	75	70	75	70
F_{su}, ksi	57	54	57	54	57	54	57	54
F_{bru}, ksi:								
(e/D = 1.5)	...	...	...	...	...	...	...	...
(e/D = 2.0)	200	190	200	190	200	190	200	190
F_{bry}, ksi:								
(e/D = 1.5)	...	...	...	...	...	...	...	...
(e/D = 2.0)	129	120	129	120	129	120	129	120
e, percent	See Table 2.3.1.0(d)							
E, 10^3 ksi	29.0							
E_c, 10^3 ksi	29.0							
G, 10^3 ksi	11.0							
μ	0.32							
Physical Properties:								
ù , lb/in.^{3}	0.283							
C, K, and á	See Figure 2.3.1.0							

a Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.
b There is no statistical basis (T_{99} or T_{90}) or specification basis (S) to support the mechanical property values in this table. See Sections 2.3.0.2.5 and 2.3.0.2.5.1.

Table 2.3.1.0(h_2). Design Mechanical and Physical Properties of Low-Alloy Steels

Alloy	4330V	See steels listed in Table 2.3.0.2 for the applicable strength levels					
Specification	AMS 6427	See Tables 2.3.1.0(a) and (b)					
Form	All wrought forms						
Condition	Quenched and tempered[a]						
Thickness or diameter, in.	# 2.5	b					c
Basis	d						
Mechanical Properties:							
F_{tu}, ksi	220	125	140	150	160	180	200
F_{ty}, ksi	185	100	120	132	142	163	176
F_{cy}, ksi	193	109	131	145	154	173	181
F_{su}, ksi	132	75	84	90	96	108	120
F_{bru}, ksi:							
(e/D = 1.5)	297	209	209	219	230	250	272
(e/D = 2.0)	385	251	273	287	300	326	355
F_{bry}, ksi:							
(e/D = 1.5)	267	146	173	189	202	230	255
(e/D = 2.0)	294	175	203	218	231	256	280
e, percent:	10	See Table 2.3.1.0(e)					
L	5[a]						
LT							
E, 10^3 ksi	29.0						
E_c, 10^3 ksi	29.0						
G, 10^3 ksi	11.0						
μ	0.32						
Physical Properties:							
ù , lb/in.^{3}	0.283						
C, K, and á	See Figure 2.3.1.0						

a Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

b For F_{tu} # 180 ksi, thickness # 0.50 in. for AISI 4130 and 8630; # 0.80 in. for AISI 8735, 4135, and 8740; # 1.00 in. for AISI 4140; # 1.70 in. for AISI 4340, 4330V, 4335V, and Hy-Tuf [Quenched in molten salt at desired tempering temperature (martempering)]; # 2.50 in. for AISI 4340, 4330V, 4335V, and Hy-Tuf (Quenched in oil at a flow rate of 200 feet/min.); # 3.50 in. for AISI 4340 (Quenched in water at a flow rate of 200 feet/min.); # 5.00 in. for D6AC (Quenched in oil at a flow rate of 200 feet/min.)

c For F_{tu} = 200 ksi AISI 4130, 8630, 4135, 8740 not available; thickness # 0.80 in. for AISI 8740; # 1.00 in. for AISI 4140; # 1.70 in. for AISI 4340, 4330V, 4335V, and Hy-Tuf [Quenched in molten salt at desired tempering temperature (martempering)]; # 2.50 in. for AISI 4340, 4330V, 4335V, and Hy-Tuf (Quenched in oil at a flow rate of 200 feet/min.); # 3.50 in. for AISI 4340 (Quenched in water at a flow rate of 200 feet/min.); # 5.00 in. for D6AC (Quenched in oil at a flow rate of 200 feet/min.)

d There is no statistical basis (T_{99} or T_{90}) or specification basis (S) to support the mechanical property values in this table. See Sections 2.3.0.2.5 and 2.3.0.2.5.1.

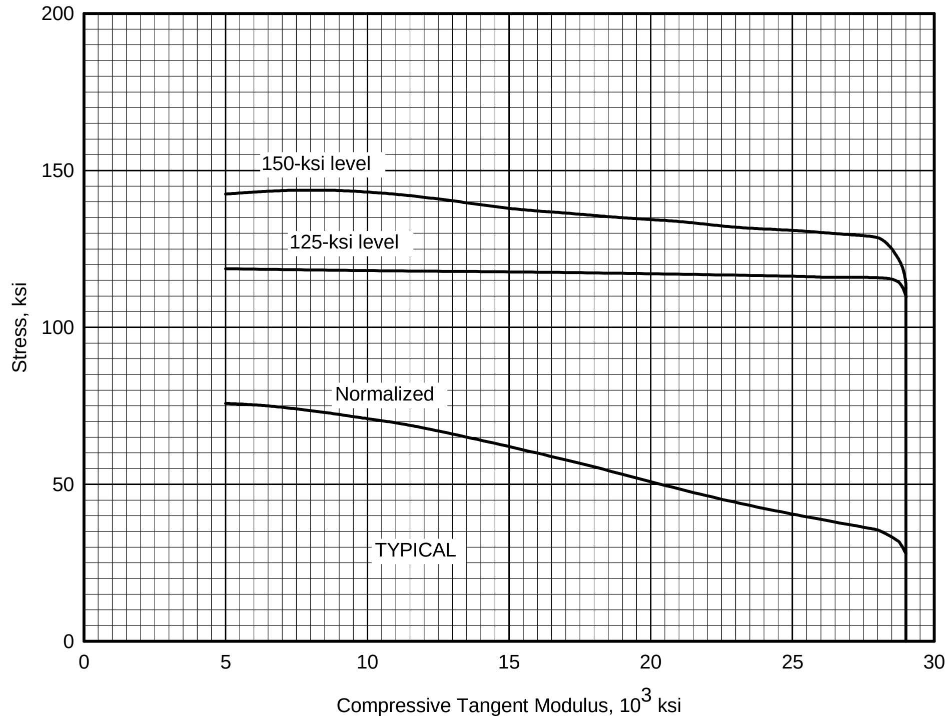

Figure 2.3.1.2.6(b). Typical compressive tangent-modulus curves at room temperature for heat-treated AISI 8630 alloy steel (all products).

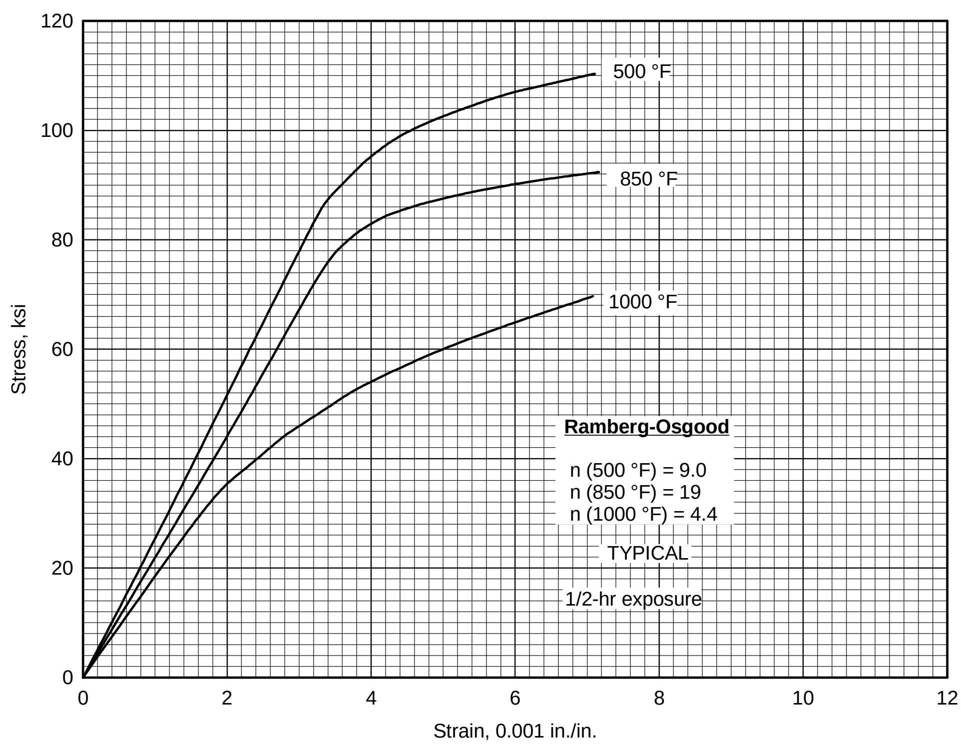

Figure 2.3.1.2.6(c). Typical tensile stress-strain curves at elevated temperatures for heat-treated AISI 8630 alloy steel, F_{tu} = 125 ksi (all products).

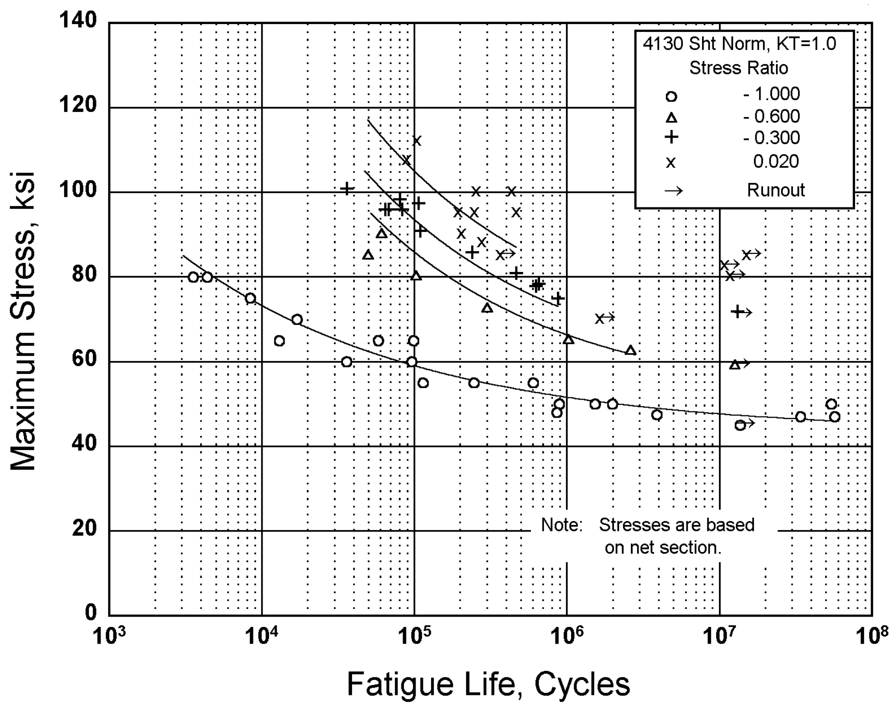

Figure 2.3.1.2.8(a). Best-fit S/N curves for unnotched 4130 alloy steel sheet, normalized, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(a)

Product Form: Sheet, 0.075-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
117	99	RT

Specimen Details: Unnotched
2.88-3.00 inches gross width
0.80-1.00 inch net width
12.0 inch net section radius

Surface Condition: Electropolished

References: 3.2.3.1.8(a) and (f)

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

Test Parameters:
Loading - Axial
Frequency - 1100-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equations:

For stress ratios of -0.60 to +0.02
Log N_f = 9.65-2.85 log (S_{eq} - 61.3)
$S_{eq} = S_{max}\,(1-R)^{0.41}$
Std. Error of Estimate, Log (Life) = 0.21
Standard Deviation, Log (Life) = 0.45
R^2 = 78%

Sample Size = 23

For a stress ratio of -1.0
Log N_f = 9.27-3.57 log (S_{max}-43.3)

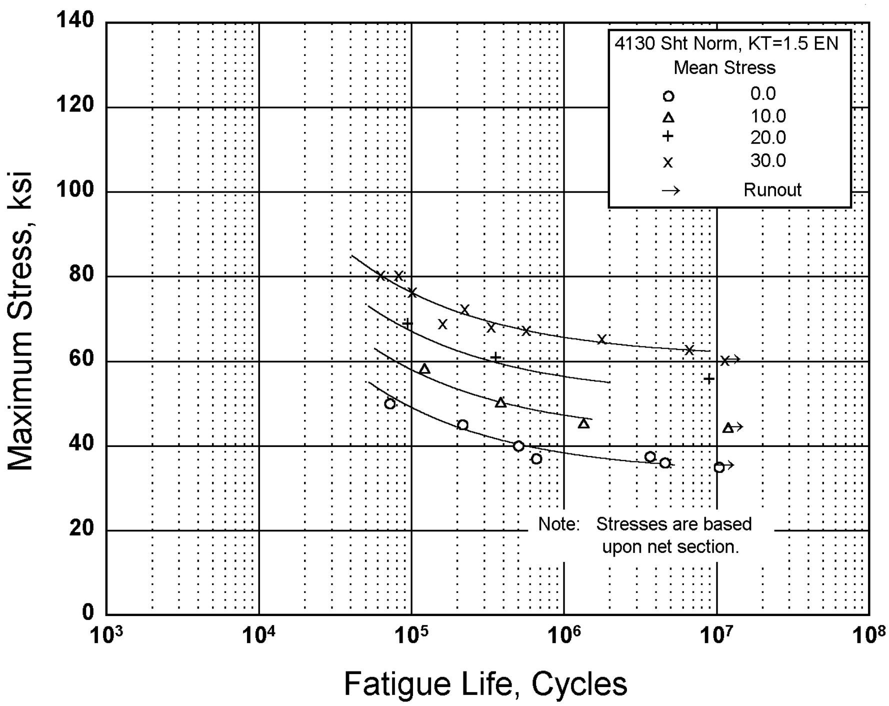

Figure 2.3.1.2.8(b). Best-fit S/N curves for notched, K_t = 1.5, 4130 alloy steel sheet, normalized, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(b)

Product Form: Sheet, 0.075-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
117	99	RT (unnotched)
123	--	RT (notched) K_t 1.5

Specimen Details: Edge Notched, K_t = 1.5
3.00 inches gross width
1.50 inches net width
0.76-inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(d)

Test Parameters:
Loading - Axial
Frequency - 1100-1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equations:

$\text{Log } N_f = 7.94 - 2.01 \log (S_{eq} - 61.3)$
$S_{eq} = S_{max} (1-R)^{0.88}$
Std. Error of Estimate, Log (Life) = 0.27
Standard Deviation, Log (Life) = 0.67
R^2 = 84%

Sample Size = 21

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

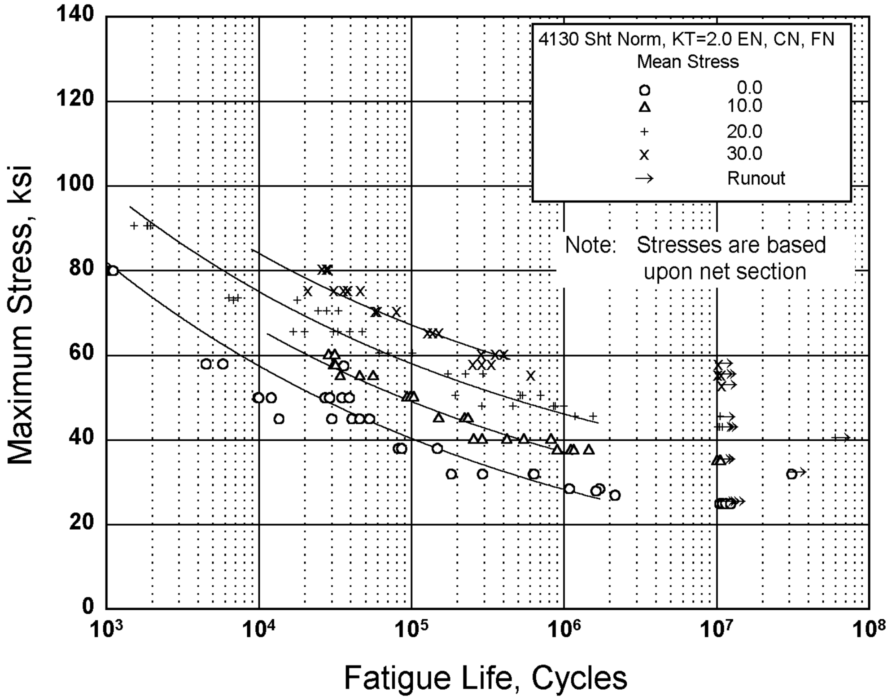

Figure 2.3.1.2.8(c). Best-fit S/N curves for notched, K_t = 2.0, 4130 alloy steel sheet, normalized, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(c)

Product Form: Sheet, 0.075-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
117	99	RT (unnotched)
120	--	RT (notched) K_t 2.0

Specimen Details: Notched, K_t = 2.0

Notch Type	Gross Width	Net Width	Notch Radius
Edge	2.25	1.500	0.3175
Center	4.50	1.500	1.500
Fillet	2.25	1.500	0.1736

Surface Condition: Electropolished

References: 3.2.3.1.8(b) and (f)

Test Parameters:
Loading - Axial
Frequency - 1100-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 17.1-6.49 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.86}$
Std. Error of Estimate, Log (Life) = 0.19
Standard Deviation, Log (Life) = 0.78
R^2 = 94%

Sample Size = 107

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

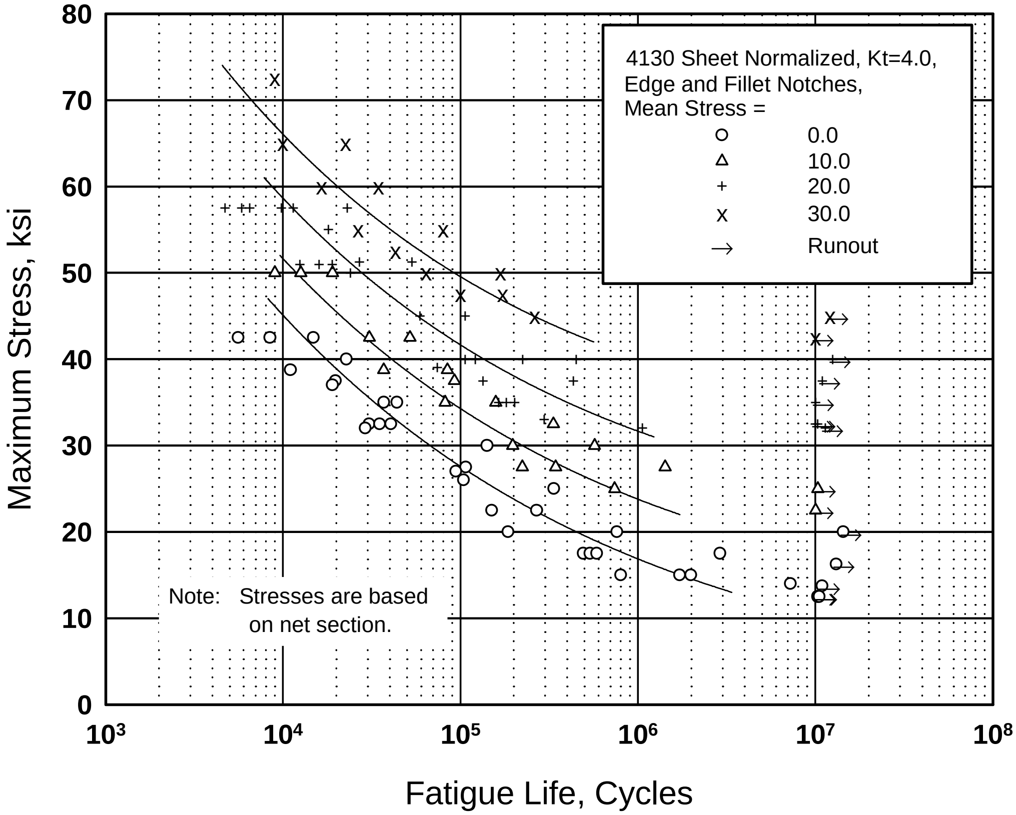

Figure 2.3.1.2.8(d). Best-fit S/N curves diagram for notched, K_t = 4.0, 4130 alloy steel sheet, normalized, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(d)

Product Form: Sheet, 0.075-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
117	99	RT (unnotched)
120	—	RT (notched) K_t = 4.0

Specimen Details: Notched, K_t = 4.0

Notch Type	Gross Width	Net Width	Notch Radius
Edge	2.25	1.500	0.057
Edge	4.10	1.496	0.070
Fillet	2.25	1.500	0.0195

Surface Condition: Electropolished

References: 3.2.3.1.8(b), (f), and (g)

Test Parameters:
Loading - Axial
Frequency - 1100-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 12.6-4.69 log (S_{eq})
$S_{eq} = S_{max}\ (1\text{-}R)^{0.63}$
Std. Error of Estimate, Log (Life) = 0.24
Standard Deviation, Log (Life) = 0.70
R^2 = 88%

Sample Size = 87

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

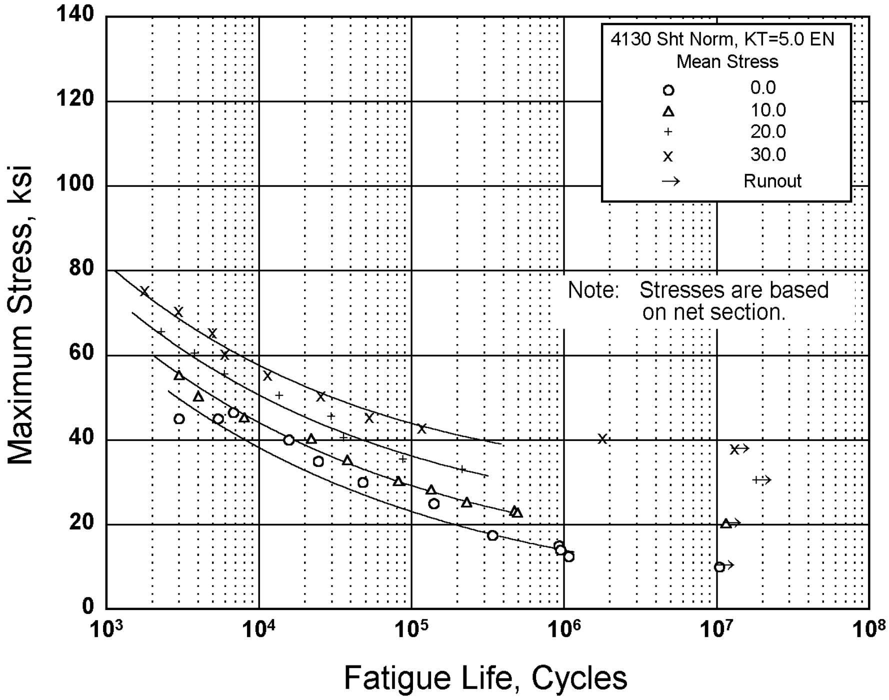

Figure 2.3.1.2.8(e). Best-fit S/N curves diagram for notched, K_t = 5.0, 4130 alloy steel sheet, normalized, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(e)

Product Form: Sheet, 0.075-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
117	99	RT (unnotched)
120	—	RT (notched) K_t = 5.0

Specimen Details: Edge Notched, K_t = 5.0
Gross width = 2.25 inches
Net width = 1.50 inches
Notch radius = 0.075 inch

Surface Condition: Electropolished

Reference: 3.2.3.1.8(c)

Test Parameters:
Loading - Axial
Frequency - 1100-1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 12.0-4.57 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.56}$
Std. Error of Estimate, Log (Life) = 0.18
Standard Deviation, Log (Life) = 0.87
R^2 = 96%

Sample Size = 38

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

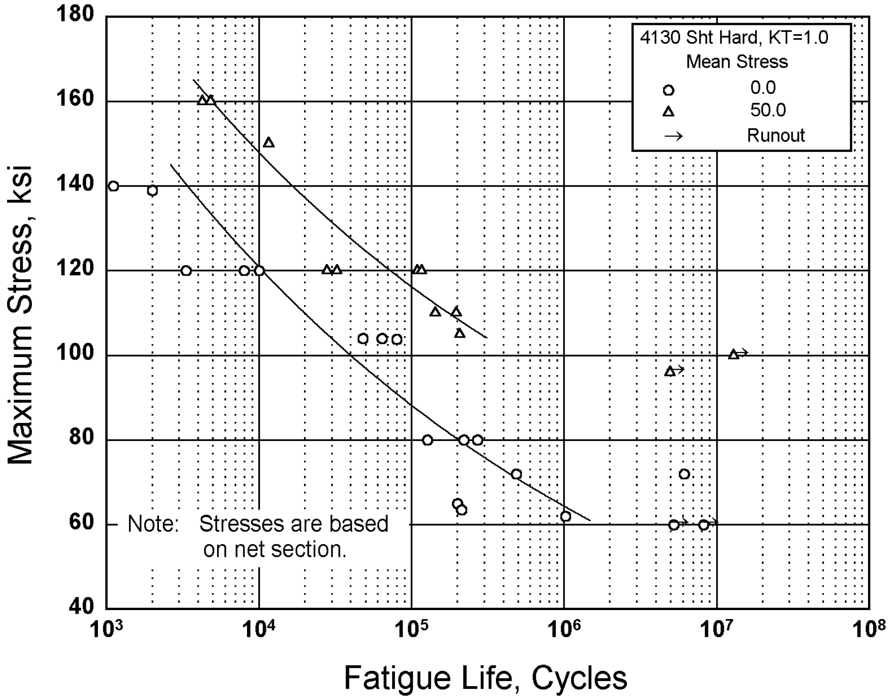

Figure 2.3.1.2.8(f). Best-fit S/N curves for unnotched 4130 alloy steel sheet, F_{tu} = 180 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(f)

Product Form: Sheet, 0.075-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
180	174	RT

Specimen Details: Unnotched
2.88 inches gross width
1.00 inch net width
12.0 inch net section radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(f)

Test Parameters:
Loading - Axial
Frequency - 20-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 20.3-7.31 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.49}$
Std. Error of Estimate, Log (Life) = 0.39
Standard Deviation, Log (Life) = 0.89
R^2 = 81%

Sample Size = 27

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

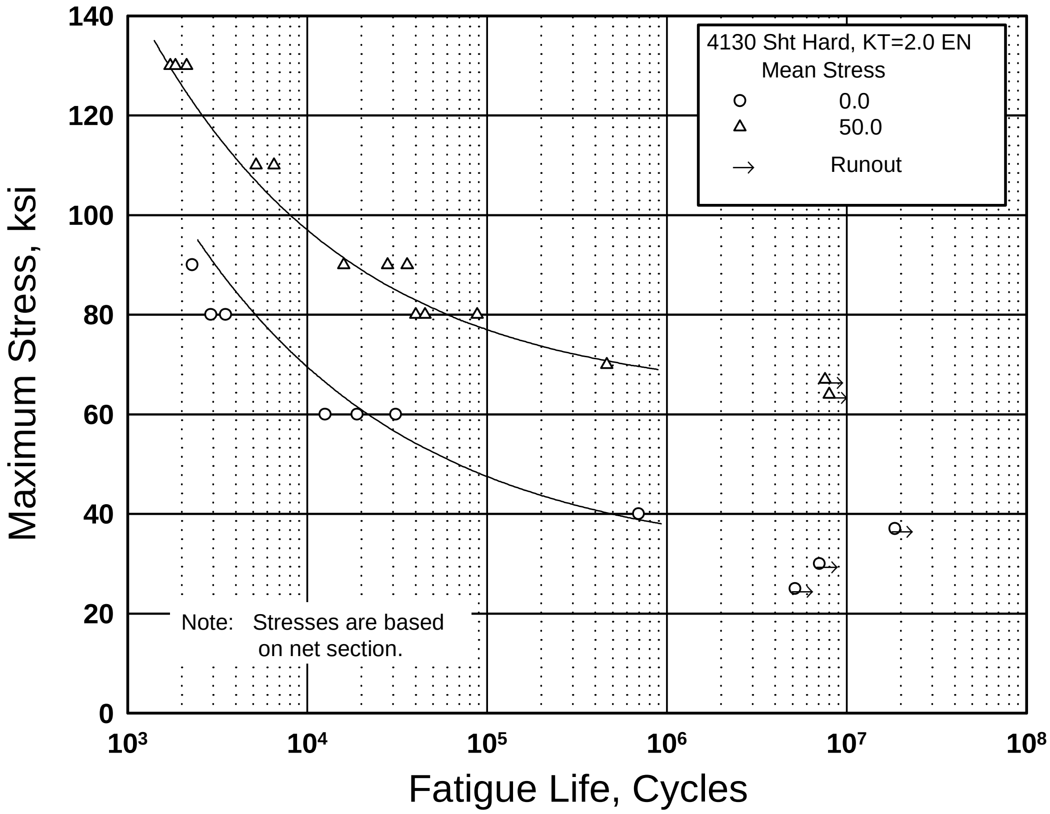

Figure 2.3.1.2.8(g). Best-fit S/N curves for notched, K_t = 2.0, 4130 alloy steel sheet, F_{tu} = 180 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(g)

Product Form: Sheet, 0.075-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
180	174	RT

Specimen Details: Edge Notched
2.25 inches gross width
1.50 inches net width
0.3175-inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(f)

Test Parameters:
Loading - Axial
Frequency - 21-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 8.87-2.81 log (S_{eq} - 41.5)
$S_{eq} = S_{max} (1-R)^{0.46}$
Std. Error of Estimate, Log (Life) = 0.18
Standard Deviation, Log (Life) = 0.77
R^2 = 94%

Sample Size = 19

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

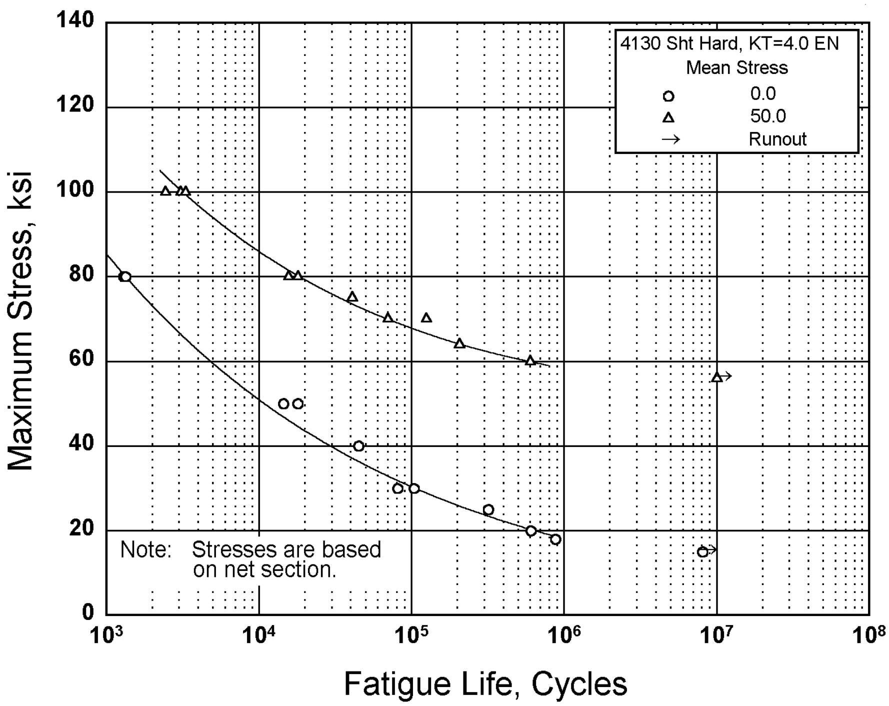

Figure 2.3.1.2.8(h). Best-fit S/N curves for notched, K_t = 4.0, 4130 alloy steel sheet, F_{tu} = 180 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.2.8(h)

Product Form: Sheet, 0.075-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
180	174	RT

Specimen Details: Edge Notched
2.25 inches gross width
1.50 inches net width
0.057-inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(f)

Test Parameters:
Loading - Axial
Frequency - 23-1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

Log N_f = 12.4-4.45 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.60}$
Std. Error of Estimate, Log (Life) = 0.11
Standard Deviation, Log (Life) = 0.90
R^2 = 98%

Sample Size = 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

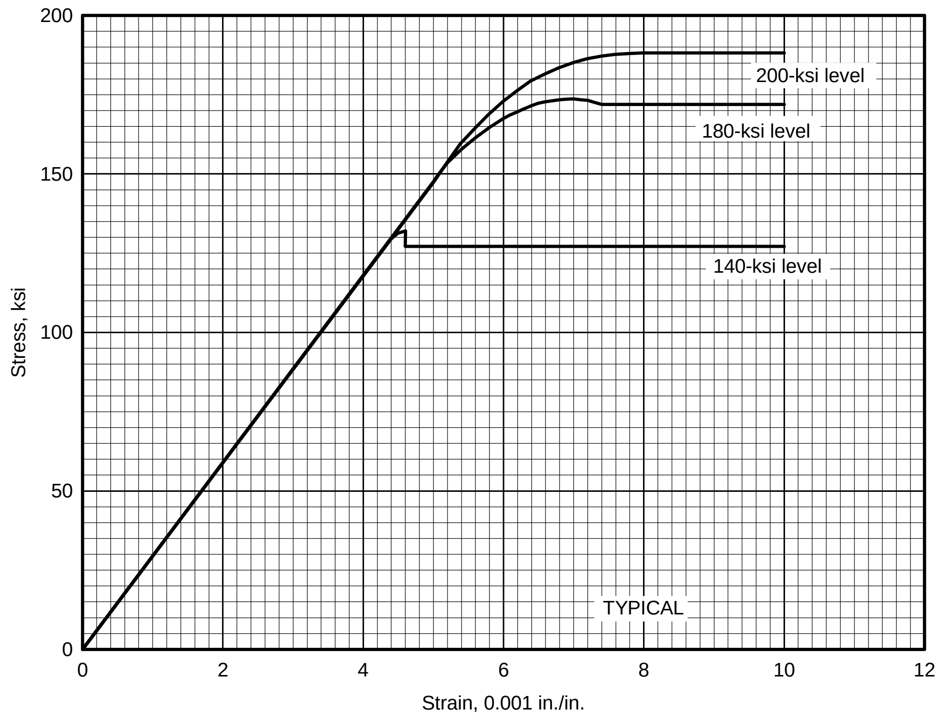

Figure 2.3.1.3.6(a). Typical tensile stress-strain curves at room temperature for heat-treated AISI 4340 alloy steel (all products).

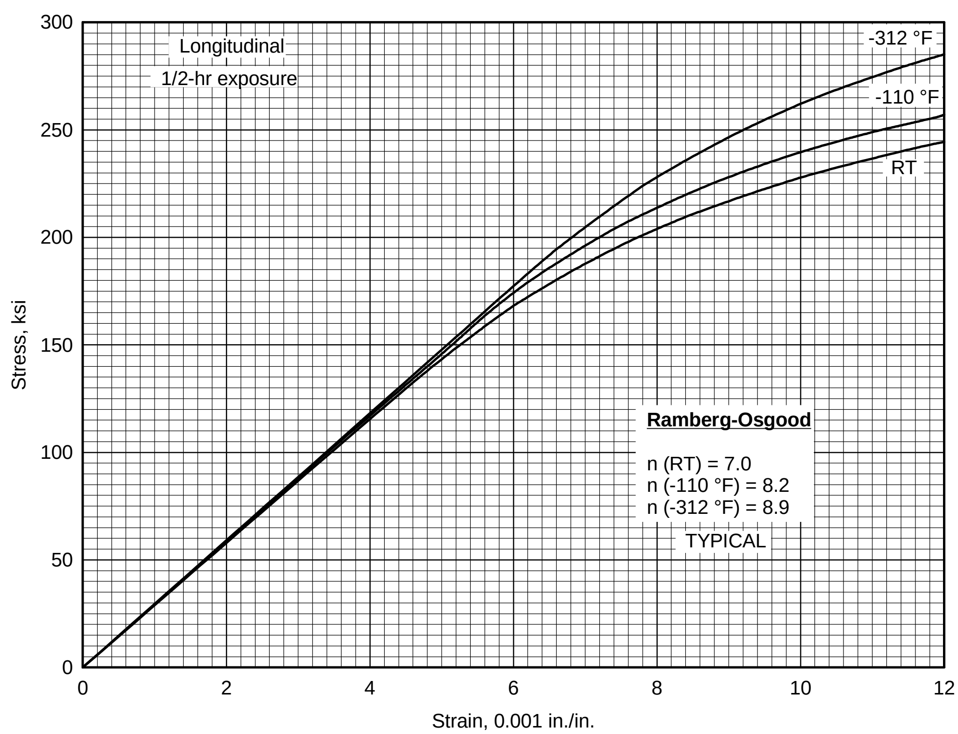

Figure 2.3.1.3.6(b). Typical tensile stress-strain curves at cryogenic and room temperature for AISI 4340 alloy steel bar, F_{tu} = 260 ksi.

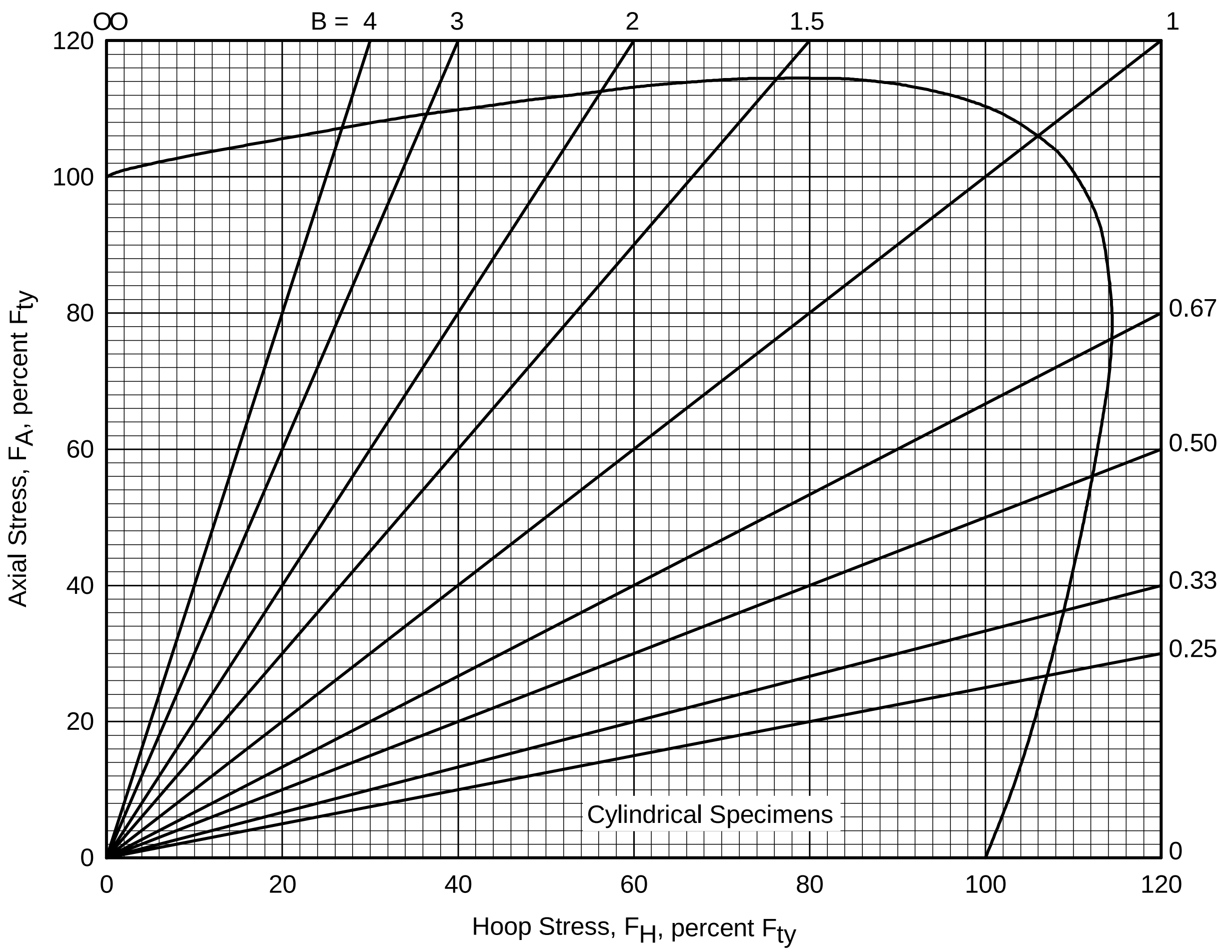

Figure 2.3.1.3.6(g). Biaxial yield-stress envelope at room temperature for AISI 4340 alloy steel (machined thin-wall cylinders, axial direction = longitudinal direction of bar stock), F_{tu} = 260 ksi, F_{ty} measured in the hoop direction.

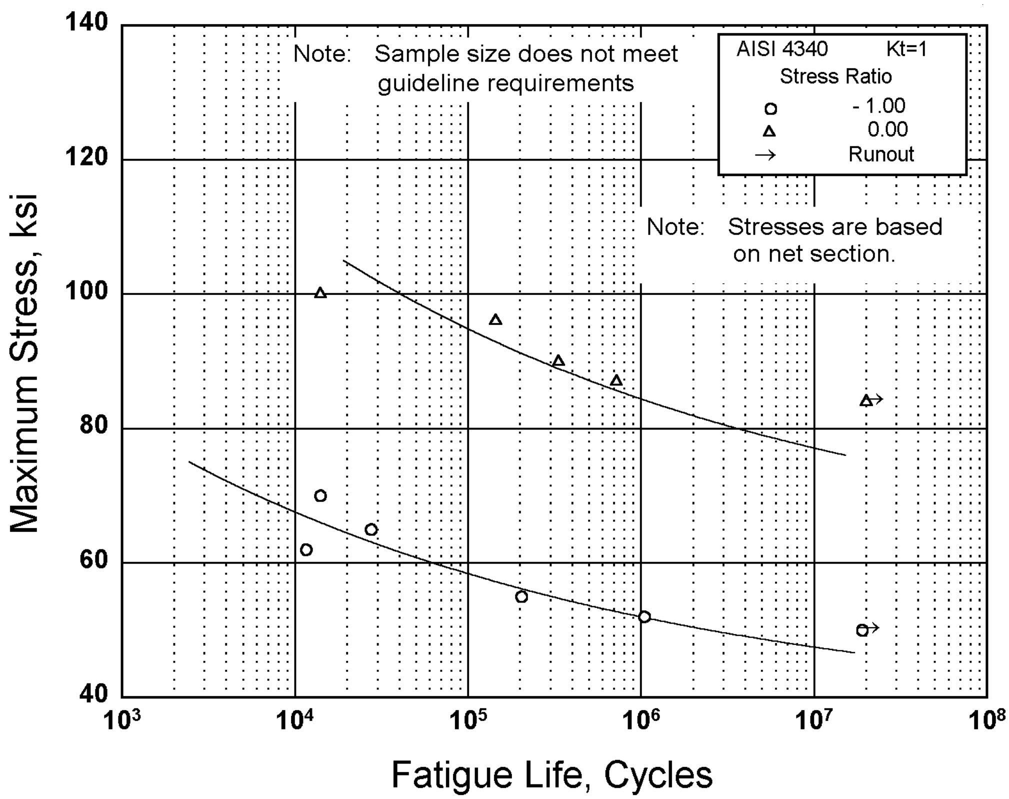

Figure 2.3.1.3.8(a). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar, F_{tu} = 125 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(a)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
125	—	RT (unnotched)
150	—	RT (notched)

Specimen Details: Unnotched
0.400-inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
Log N_f = 14.96-6.46 log (S_{eq}-60)
$S_{eq} = S_{max} (1-R)^{0.70}$
Std. Error of Estimate, Log (Life) = 0.35
Standard Deviation, Log (Life) = 0.77
R^2 = 75%

Sample Size = 9

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

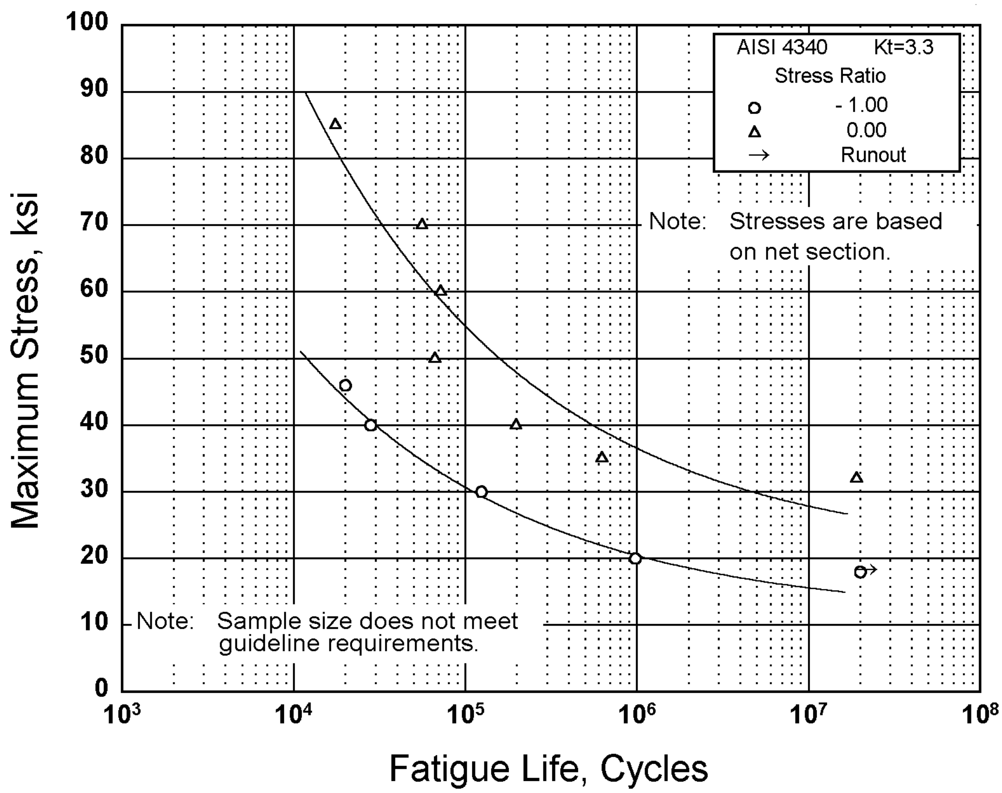

Figure 2.3.1.3.8(b). Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar, F_{tu} = 125 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(b)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
125	—	RT (unnotched)
150	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 9.75\text{-}3.08 \log (S_{eq}\text{-}20.0)$
$S_{eq} = S_{max} (1\text{-}R)^{0.84}$
Std. Error of Estimate, Log (Life) = 0.40
Standard Deviation, Log (Life) = 0.90
R^2 = 80%

Sample Size = 11

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

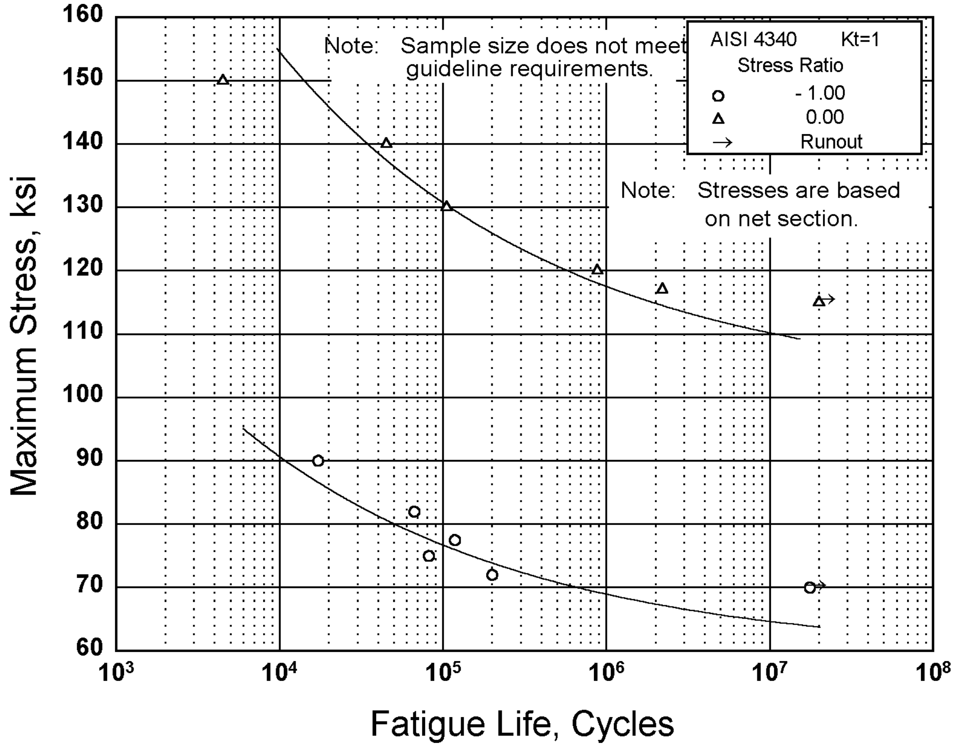

Figure 2.3.1.3.8(c). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(c)

Product Form: Rolled bar, 1.125 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
190	—	RT (notched)

Specimen Details: Unnotched
0.400-inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
Log N_f = 10.76-3.91 log (S_{eq} - 101.0)
$S_{eq} = S_{max} (1-R)^{0.77}$
Std. Error of Estimate, Log (Life) = 0.17
Standard Deviation, Log (Life) = 0.33
Adjusted R^2 Statistic = 73%

Sample Size = 9

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

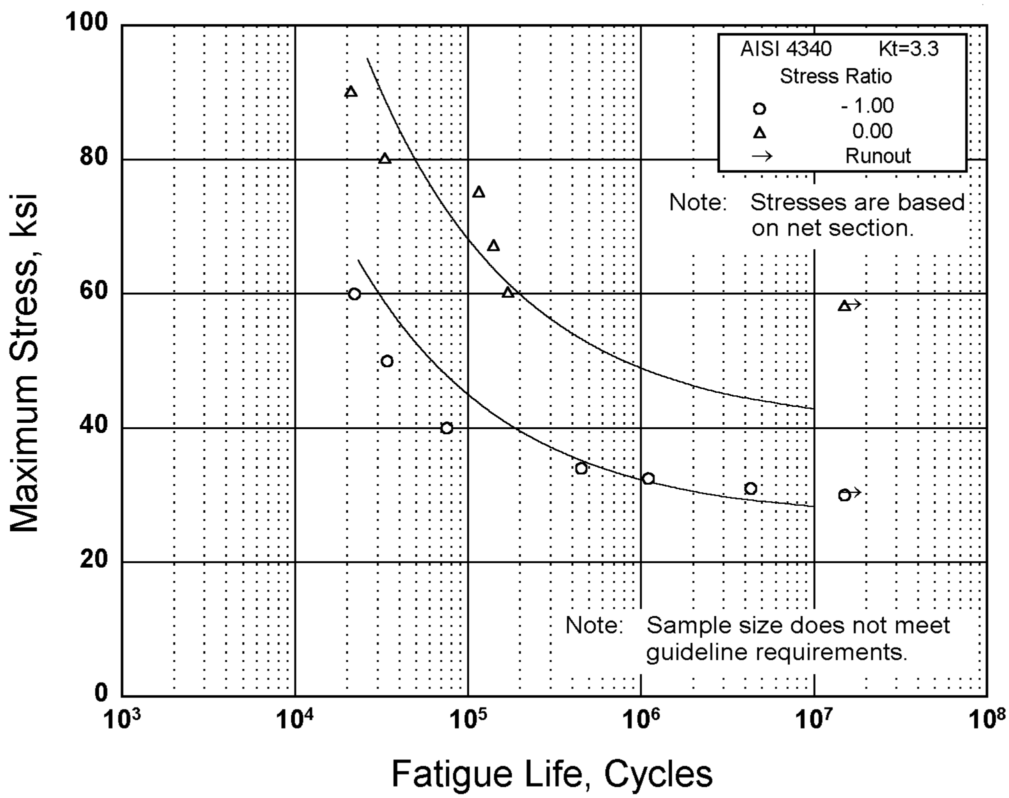

Figure 2.3.1.3.8(d). Best-fit S/N curves for notched AISI 4340 alloy steel bar, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(d)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
190	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
Log N_f = 7.90-2.00 log (S_{eq}-40.0)
$S_{eq} = S_{max} (1-R)^{0.60}$
Std. Error of Estimate, Log (Life) = 0.27
Standard Deviation, Log (Life) = 0.74
R^2 = 86%

Sample Size = 11

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

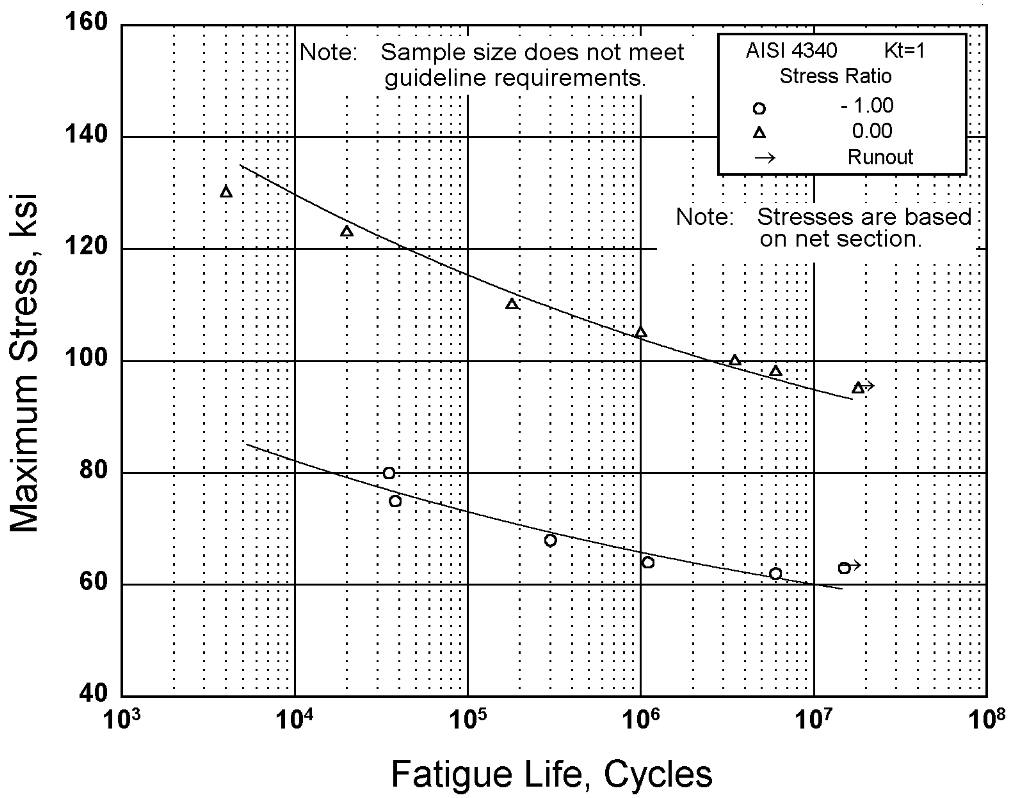

Figure 2.3.1.3.8(e). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar at 600°F, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(e)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
153	121	600 (unnotched)
190	—	RT (notched)
176	—	600 (notched)

Specimen Details: Unnotched
0.400-inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 600°F
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 22.36\text{-}9.98 \log (S_{eq}\text{-}60.0)$
$S_{eq} = S_{max} (1\text{-}R)^{0.66}$
Std. Error of Estimate Log (Life) = 0.24
Standard Deviation, Log (Life) = 1.08
R^2 = 95%

Sample Size = 11

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

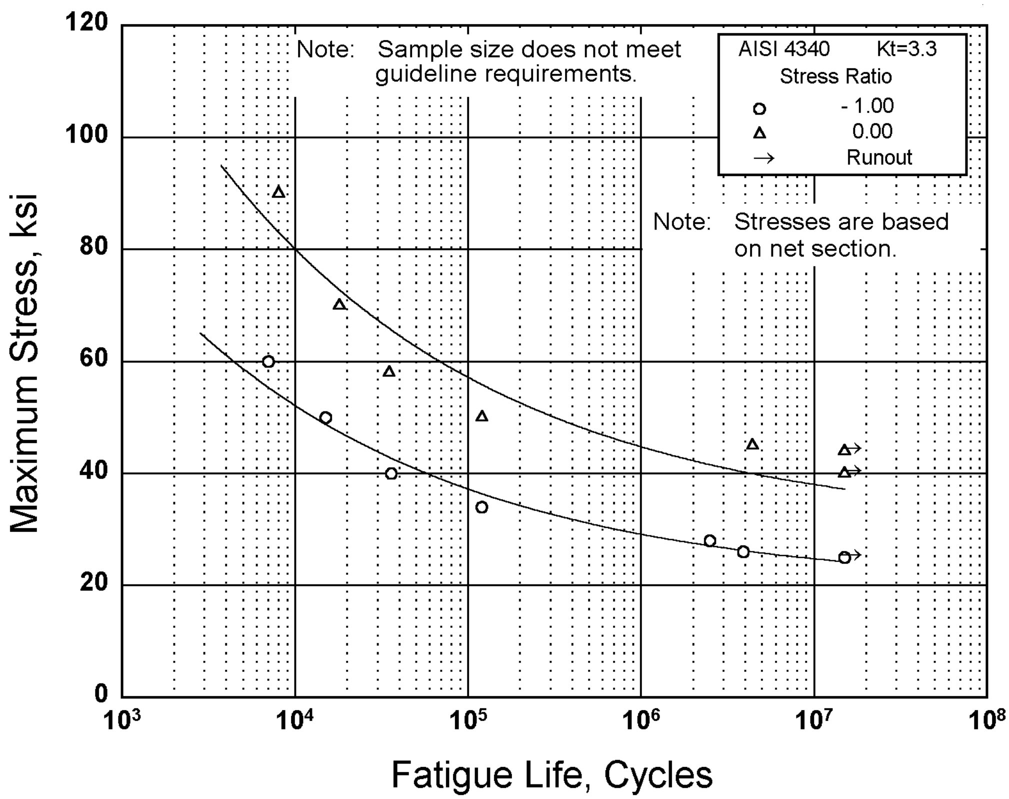

Figure 2.3.1.3.8(f). Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar at 600°F, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(f)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
153	121	600 (unnotched)
190	—	RT (notched)
176	—	600 (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
Log N_f = 10.39-3.76 log (S_{eq}-30.0)
$S_{eq} = S_{max}$ (1-R)$^{0.62}$
Std. Error of Estimate, Log (Life) = 0.36
Standard Deviation, Log (Life) = 1.06
R^2 = 89%

Sample Size = 11

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

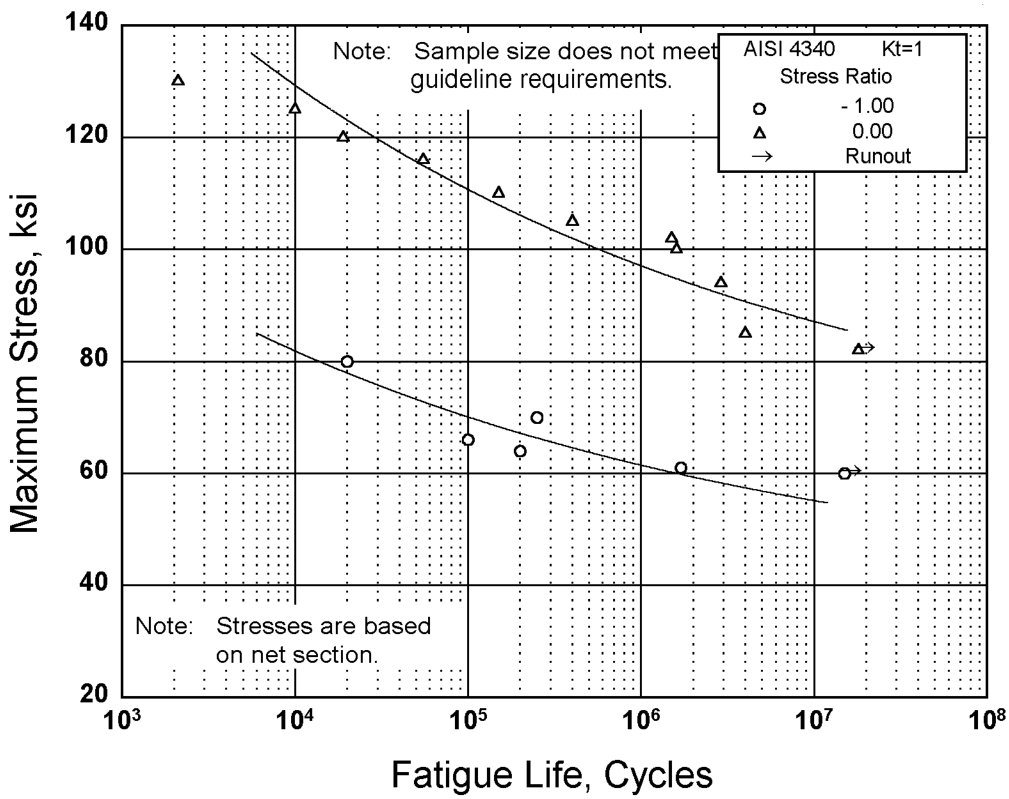

Figure 2.3.1.3.8(g). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar at 800°F, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(g)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
125	101	800 (unnotched)
190	—	RT (notched)
154	—	800 (notched)

Specimen Details: Unnotched
0.400-inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 800°F
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 17.53\text{-}7.35 \log (S_{eq}\text{-}60.0)$
$S_{eq} = S_{max} (1\text{-}R)^{0.66}$
Std. Error of Estimate, Log (Life) = 0.42
Standard Deviation, Log (Life) = 0.99
R^2 = 82%

Sample Size = 15

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

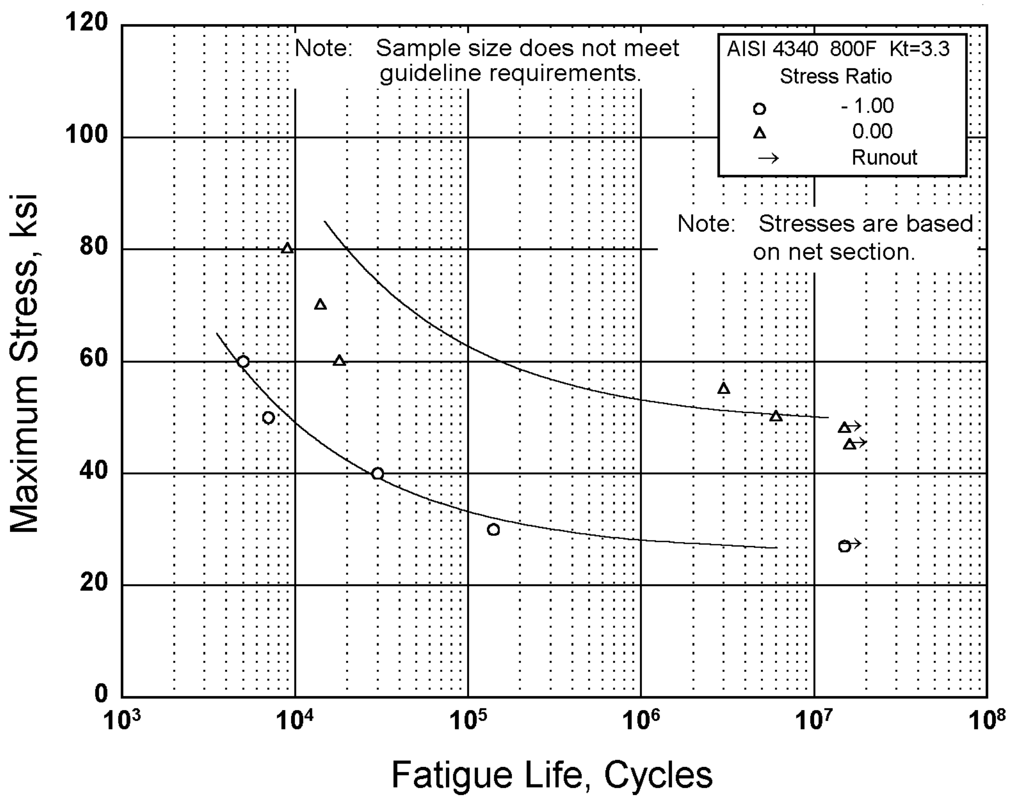

Figure 2.3.1.3.8(h). Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar at 800°F, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(h)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
125	101	800 (unnotched)
190	—	RT (notched)
154	—	800 (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 800°F
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 7.31 - 2.01 \log (S_{eq} - 48.6)$
$S_{eq} = S_{max} (1-R)^{0.92}$
Std. Error of Estimate, Log (Life) = 0.60
Standard Deviation, Log (Life) = 1.14
R^2 = 72%

Sample Size = 9

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

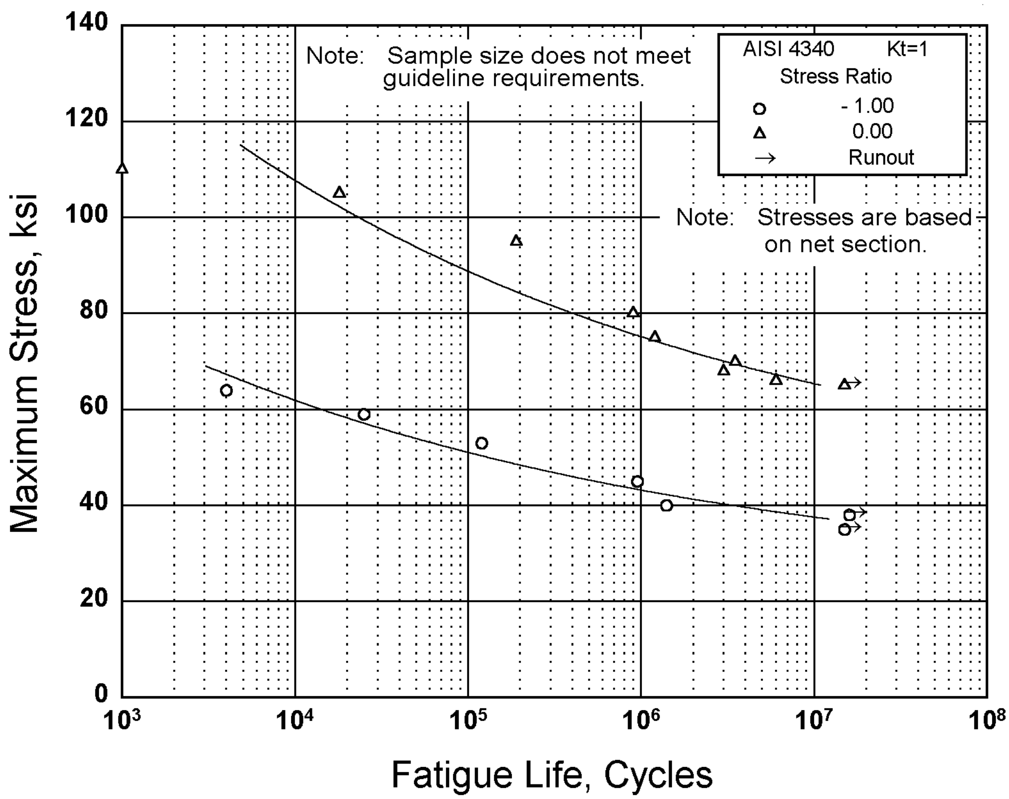

Figure 2.3.1.3.8(i). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar at 1000°F, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(i)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
81	63	1000°F (unnotched)
190	—	RT (notched)
98	—	1000°F (notched)

Specimen Details: Unnotched
0.400-inch diameter

Surface Condition: Hand polished to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 1000°F
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
Log N_f = 16.85-7.02 log (S_{eq}-40.0)
$S_{eq} = S_{max} (1-R)^{0.80}$
Std. Error of Estimate, Log (Life) = 0.42
Standard Deviation, Log (Life) = 1.20
R^2 = 88%

Sample Size = 13

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

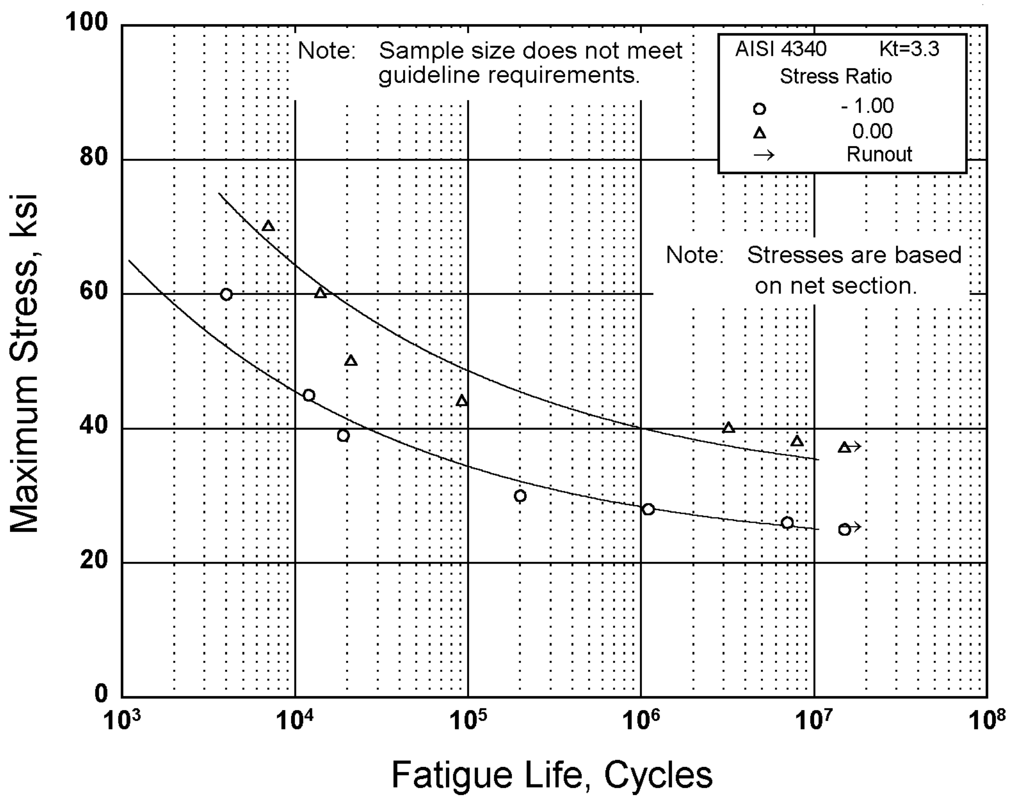

Figure 2.3.1.3.8(j). Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar at 1000°F, F_{tu} = 150 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(j)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
158	147	RT (unnotched)
81	63	1000°F (unnotched)
190	—	RT (notched)
98	—	1000°F (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(b)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - 1000°F
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 9.76\text{-}3.75 \log (S_{eq}\text{-}30.0)$
$S_{eq} = S_{max} (1\text{-}R)^{0.50}$
Std. Error of Estimate, Log (Life) = 0.40
Standard Deviation, Log (Life) = 1.22
R^2 = 89%

Sample Size = 12

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

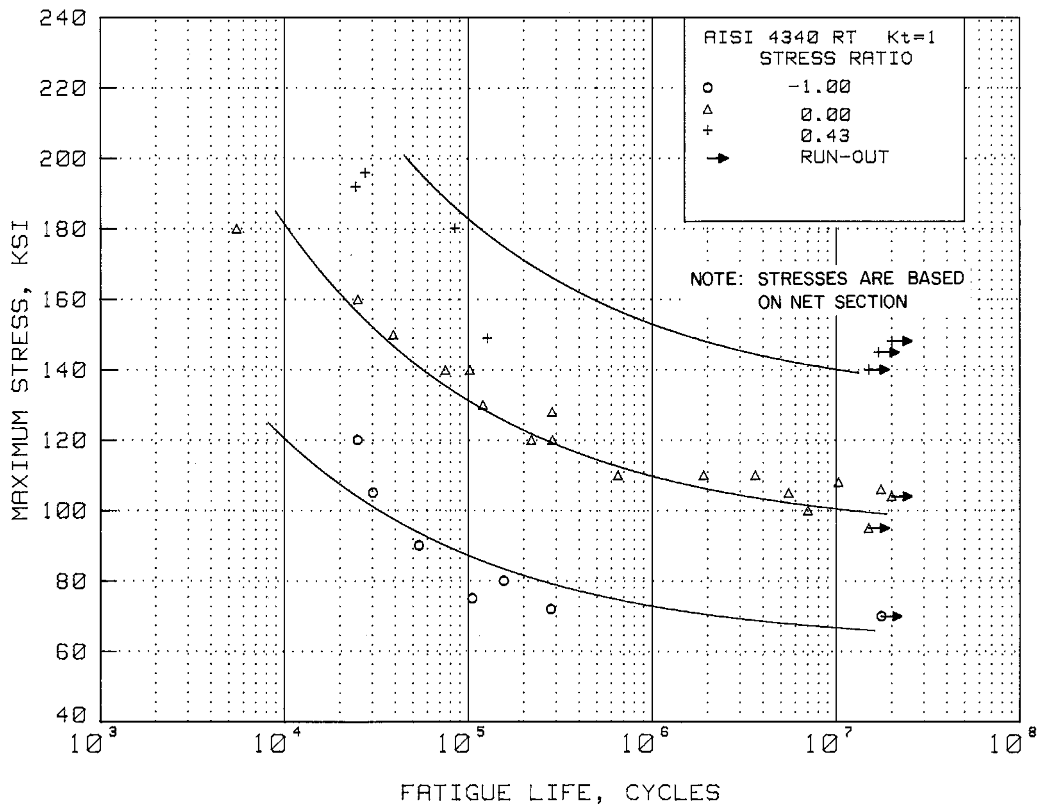

Figure 2.3.1.3.8(k). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar and die forging, F_{tu} = 200 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(k)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted
Die forging (landing gear-B36 aircraft), air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
208, 221	189, 217	RT (unnotched)
251	—	RT (notched)

Specimen Details: Unnotched
0.300 and 0.400-inch diameter

Surface Condition: Hand polished to RMS 5-10

References: 2.3.1.3.8(a) and (c)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 2

Equivalent Stress Equation:
Log N_f = 9.31-2.73 log (S_{eq}-93.4)
$S_{eq} = S_{max}$ $(1\text{-}R)^{0.59}$
Standard Error of Estimate = 0.49
Standard Deviation in Life = 0.93
R^2 = 72%

Sample Size = 26

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

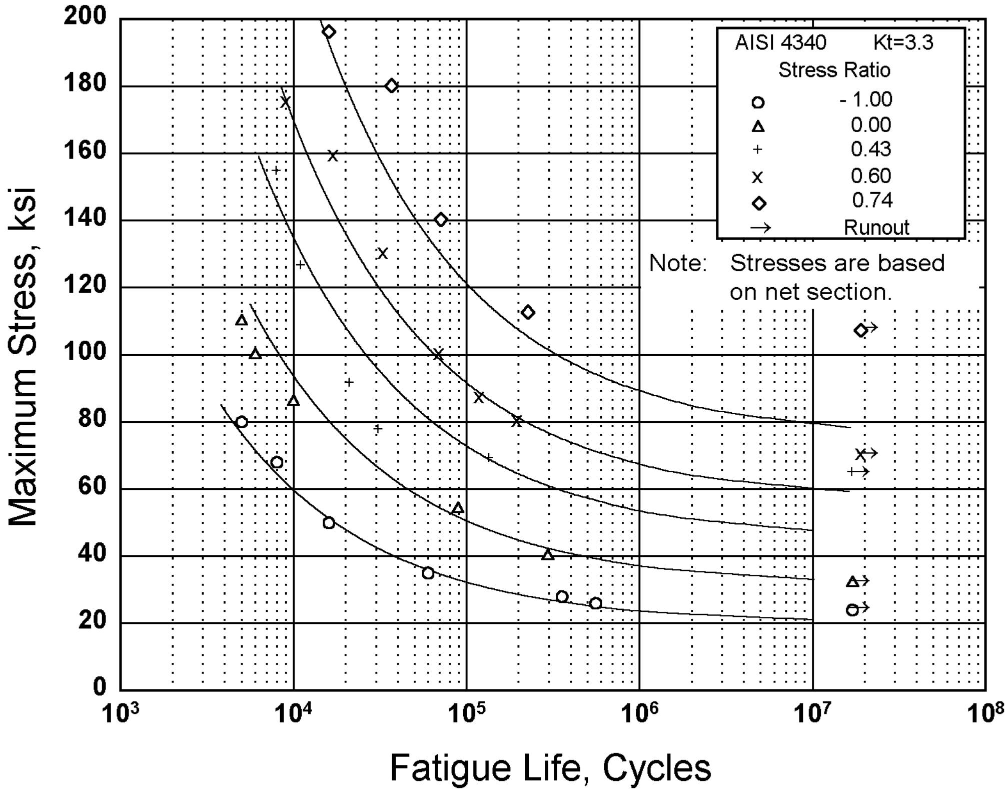

Figure 2.3.1.3.8(l). Best-fit S/N curves for notched, K_t = 3.3, AISI 4340 alloy steel bar, F_{tu} = 200 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(l)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	208	—	RT (unnotched)
	251	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.3
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 7.52\text{-}1.96 \log (S_{eq}\text{-}31.2)$
$S_{eq} = S_{max} (1\text{-}R)^{0.65}$
Std. Error of Estimate, Log (Life) = 0.16
Standard Deviation, Log (Life) = 0.62
R^2 = 93%

Sample Size = 26

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

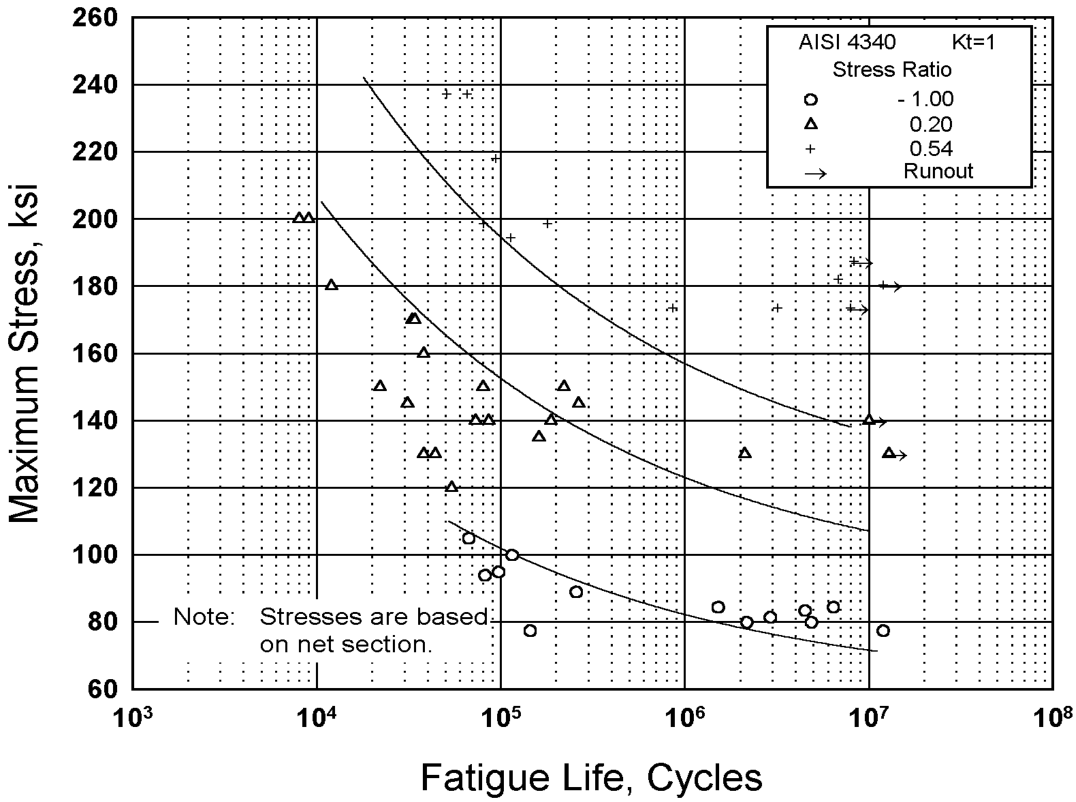

Figure 2.3.1.3.8(m). Best-fit S/N curves for unnotched AISI 4340 alloy steel bar and billet, F_{tu} = 260 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(m)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted
Billet, 6 inches RCS air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
266, 291	232	RT (unnotched)
352	—	RT (notched)

Specimen Details: Unnotched
0.200 and 0.400-inch diameter

Surface Condition: Hand polished to RMS 10

References: 2.3.1.3.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - 1800 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 2

Equivalent Stress Equation:
Log N_f = 11.62-3.75 log (S_{eq}-80.0)
$S_{eq} = S_{max} (1-R)^{0.44}$
Std. Error of Estimate, Log (Life) = 0.64
Standard Deviation, Log (Life) = 0.86
R^2 = 45%

Sample Size = 41

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

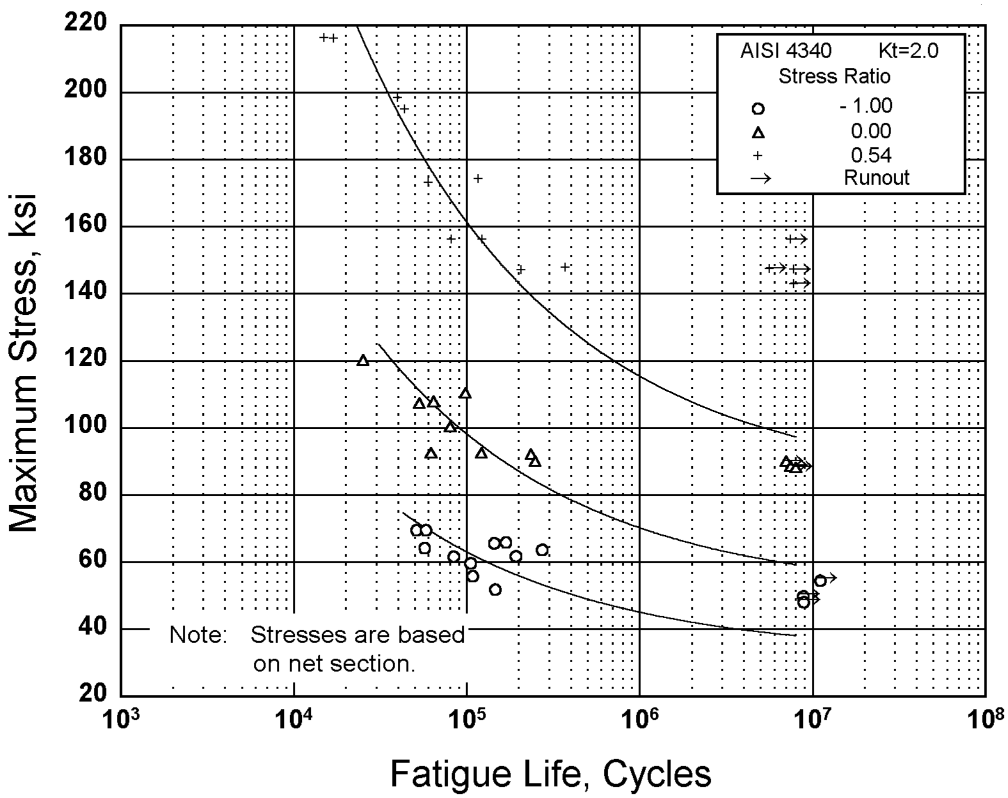

Figure 2.3.1.3.8(n). Best-fit S/N curves for notched, K_t = 2.0, AISI 4340 alloy steel bar, F_{tu} = 260 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(n)

Product Form: Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
266	232	RT (unnotched)
390	—	RT (notched)

Specimen Details: Notched, V-Groove, $K_t = 2.0$
0.300-inch gross diameter
0.220-inch net diameter
0.030-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:
Loading - Axial
Frequency - 2000 to 2500 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 1

Equivalent Stress Equation:
$\text{Log } N_f = 9.46 - 2.65 \log (S_{eq} - 50.0)$
$S_{eq} = S_{max} (1-R)^{0.64}$
Std. Error of Estimate, Log (Life) = 0.22
Standard Deviation, Log (Life) = 0.34
$R^2 = 58\%$

Sample Size = 30

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

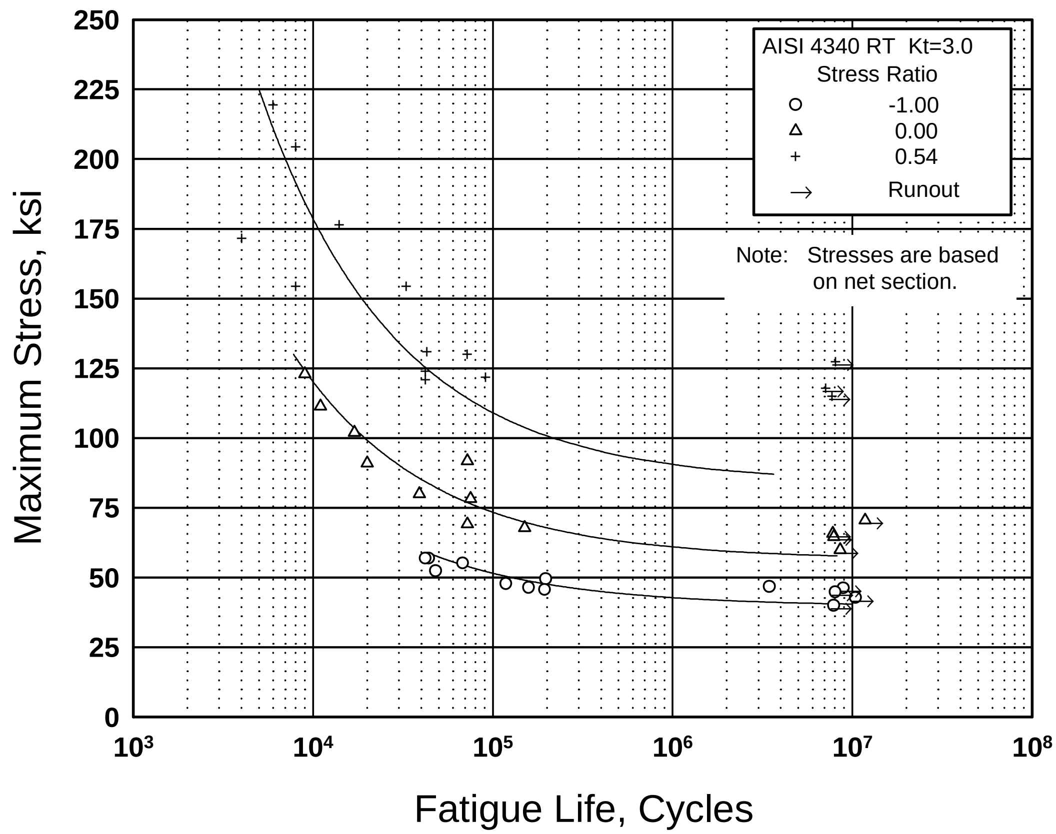

Figure 2.3.1.3.8(o). Best-fit S/N curves for notched, K_t = 3.0, AISI 4340 alloy steel bar, F_{tu} = 260 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.3.8(o)

Product Form:
Rolled bar, 1-1/8 inches diameter, air melted

Properties:

TUS, ksi	TYS, ksi	Temp., °F
266	232	RT (unnotched)
352	—	RT (notched)

Specimen Details: Notched, V-Groove, K_t = 3.0
0.270-inch gross diameter
0.220-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: Lathe turned to RMS 10

Reference: 2.3.1.3.8(a)

Test Parameters:

Loading—Axial
Frequency—2000 to 2500 cpm
Temperature—RT
Atmosphere—Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

$\text{Log } N_f = 7.14\text{-}1.74 \log (S_{eq} - 56.4)$
$S_{eq} = S_{max} (1\text{-}R)^{0.51}$
Std. Error of Estimate, Log (Life) = 0.32
Standard Deviation, Log (Life) = 0.59
R^2 = 71%

Sample Size = 29

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

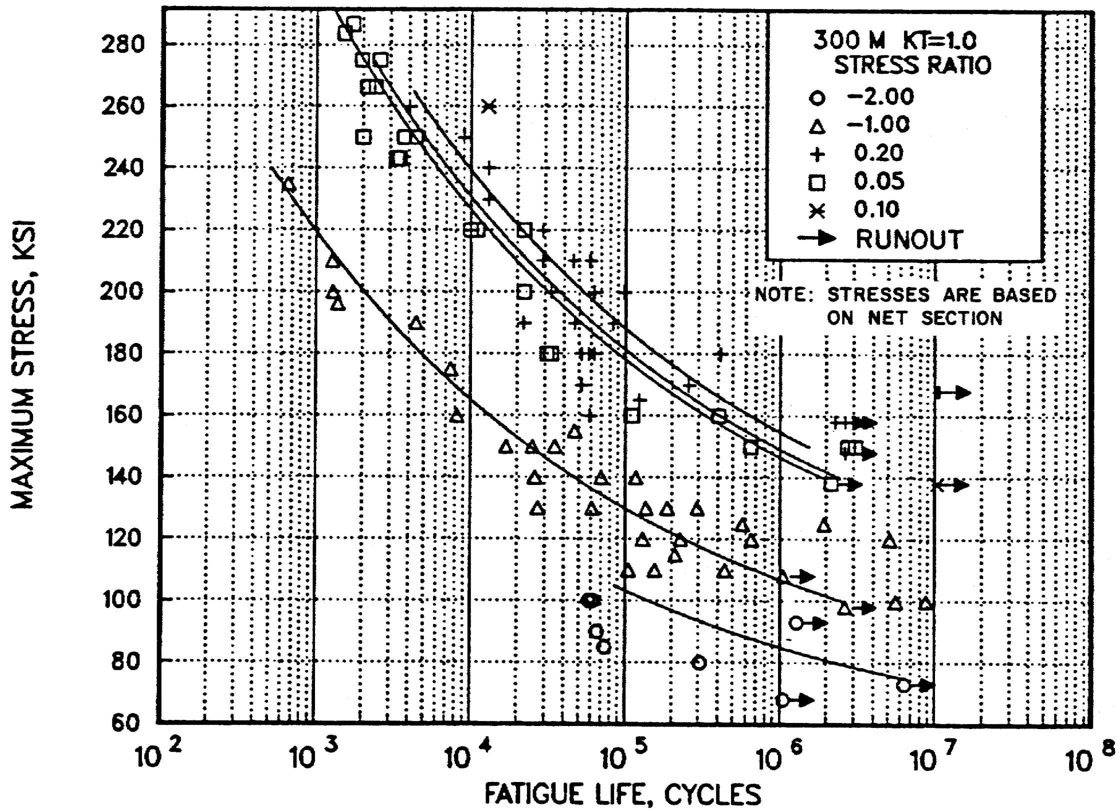

Figure 2.3.1.4.8(a). Best-fit S/N curves for unnotched 300M alloy forging, F_{tu} = 280 ksi, longitudinal and transverse directions.

Correlative Information for Figure 2.3.1.4.8(a)

Product Forms: Die forging, 10 x 20 inches CEVM
Die forging, 6-1/2 x 20 inches CEVM
RCS billet, 6 inches CEVM
Forged Bar, 1-1/4 x 8 inches CEVM

Properties:

TUS, ksi	TYS, ksi	Temp., °F
274-294	227-247	RT

Specimen Details: Unnotched
0.200 - 0.250-inch diameter

Surface Condition: Heat treat and finish grind to a surface finish of RMS 63 or better with light grinding parallel to specimen length, stress relieve

References: 2.3.1.4.8(a), (c), (d), (e)

Test Parameters:
Loading - Axial
Frequency - 1800 to 2000 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 6

Equivalent Stress Equation:
$\text{Log } N_f = 14.8 - 5.38 \log (S_{eq} - 63.8)$
$S_{eq} = S_a + 0.48\, S_m$
Std. Error of Estimate, Log (Life) = 55.7 ($1/S_{eq}$)
Standard Deviation, Log (Life) = 1.037
$R^2 = 82.0$

Sample Size = 104

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

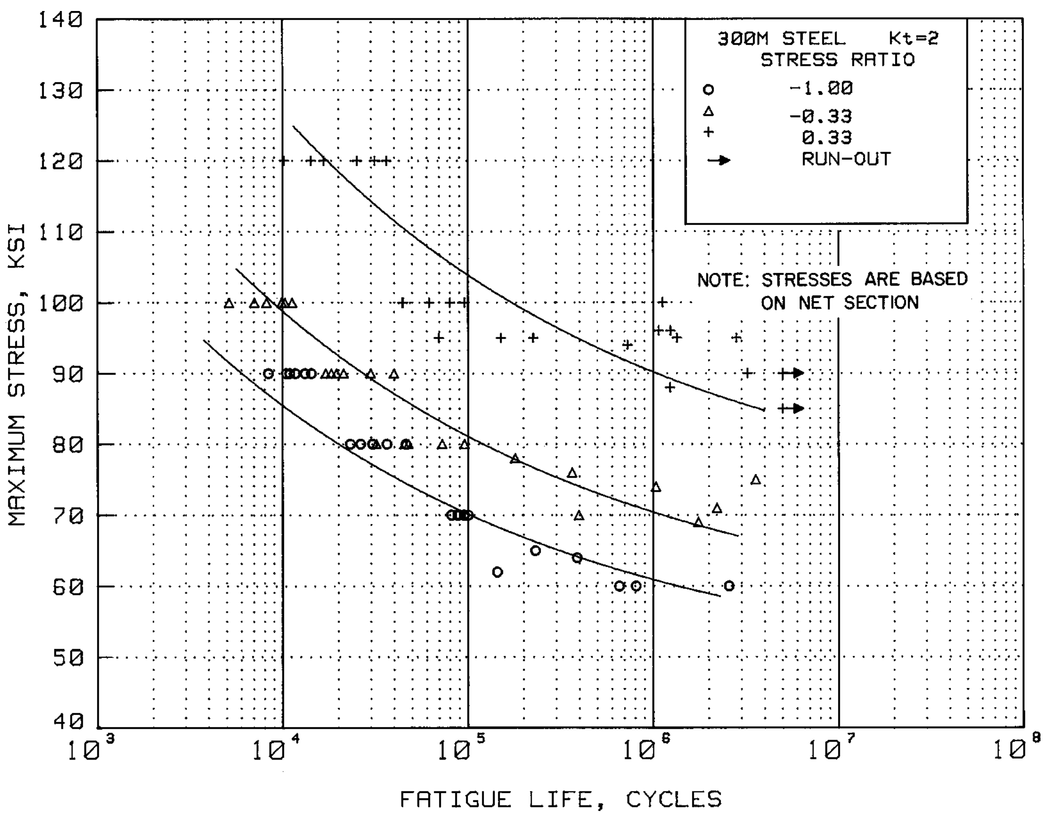

Figure 2.3.1.4.8(b). Best-fit S/N curves for unnotched, K_t = 2.0, 300M alloy forged billet, F_{tu} = 280 ksi, longitudinal direction.

Correlative Information for Figure 2.3.1.4.8(b)

Product Form: Forged billet, unspecified size, CEVM

Properties:

TUS, ksi	TYS, ksi	Temp., °F
290	242	RT (unnotched)
456	—	RT (notched)

Specimen Details: Notched, 60° V-Groove, K_t = 2.0
0.500-inch gross diameter
0.250-inch net diameter
0.040-inch root radius, r
60° flank angle, ω

Surface Condition: Heat treat and finish grind notch to RMS 63 ± 5; stress relieve

Reference: 2.3.1.4.8(b)

Test Parameters:
Loading - Axial
Frequency -
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
$\text{Log } N_f = 12.87 - 5.08 \log (S_{eq} - 55.0)$
$S_{eq} = S_{max} (1-R)^{0.36}$
Standard Deviation in Life = 0.79
R^2 = 79%

Sample Size = 70

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

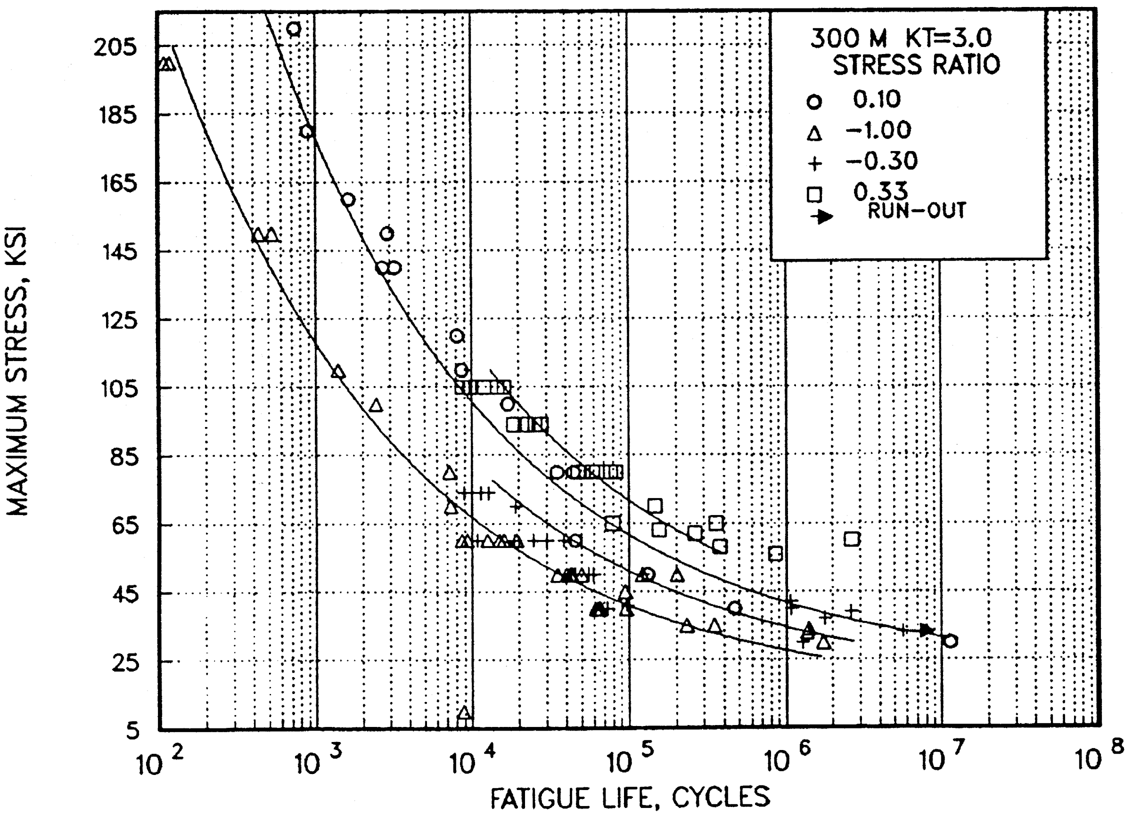

Figure 2.3.1.4.8(c). Best-fit S/N curves for notched, K_t = 3.0, 300M alloy forging, F_{tu} = 280 ksi, longitudinal and transverse directions.

Correlative Information for Figure 2.3.1.4.8(c)

Product Forms: Forged billet, unspecified size, CEVM
Die forging, 10 x 20 inches, CEVM
Die forging, 6-1/2 x 20 inches, CEVM

Properties:

TUS, ksi	TYS, ksi	Temp., °F
290-292	242-247	RT (unnotched)
435	—	RT (notched)

Specimen Details: Notched 60° V-Groove, K_t = 3.0
0.500-inch gross diameter
0.250-inch net diameter
0.0145-inch root radius, r
60° flank angle, ω

Surface Condition: Heat treat and finish grind notch to RMS 63 or better; stress relieve

References: 2.3.1.4.8(a), (b), (c)

Test Parameters:
Loading - Axial
Frequency -
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 5

Equivalent Stress Equation:
Log N_f = 10.40-3.41 log (S_{eq}-20.0)
$S_{eq} = S_{max} (1-R)^{0.51}$
Std. Error of Estimate, Log (Life) = 18.3 (1/S_{eq})
Standard Deviation, Log (Life) = 2.100
R^2 = 97.4

Sample Size = 99

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

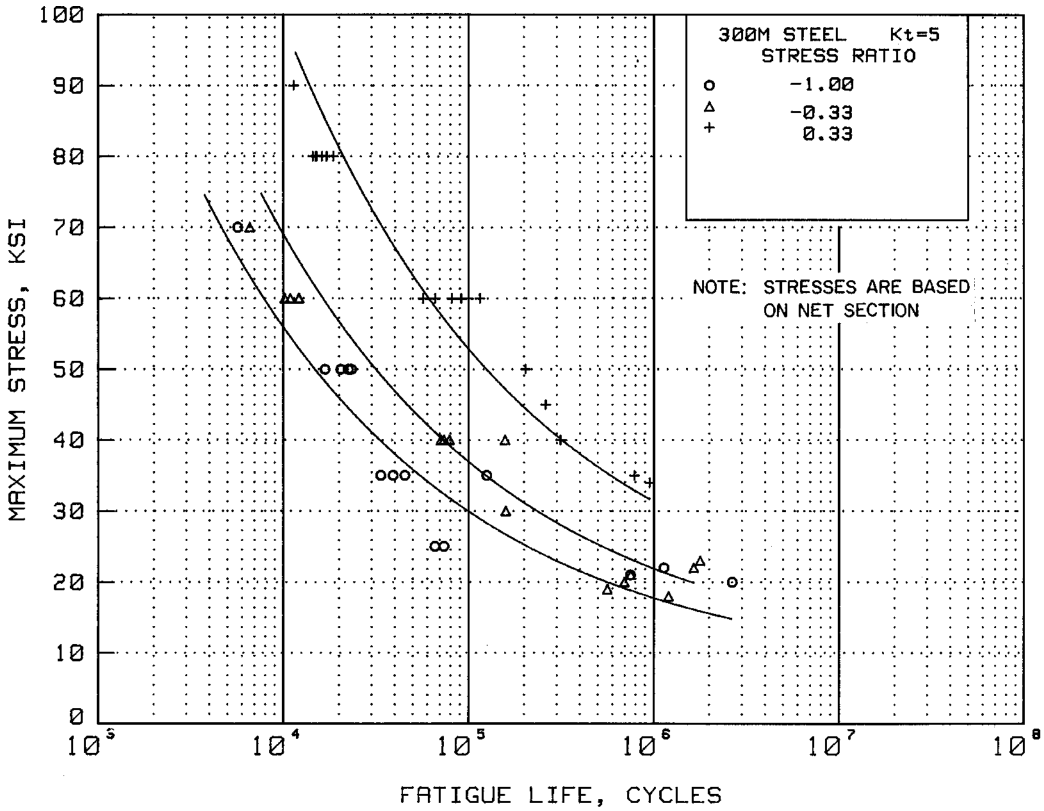

Figure 2.3.1.4.8(d). Best-fit S/N curves for notched, K_t = 5.0, 300M alloy forged billet, F_{tu} = 280 ksi, longitudinal direction.

<u>Correlative Information for Figure 2.3.1.4.8(d)</u>

<u>Product Forms</u>: Forged billet, unspecified size, CEVM

<u>Properties</u>:

	<u>TUS, ksi</u>	<u>TYS, ksi</u>	<u>Temp., °F</u>
	290	242	RT (unnotched)
	379	—	RT (notched)

<u>Specimen Details</u>: Notched, 60° V-Groove, K_t = 5.0
0.500-inch gross diameter
0.250-inch net diameter
0.0042-inch root radius, r
60° flank angle, ω

<u>Surface Condition</u>: Heat treat and finish grind notch to RMS 63 maximum; stress relieve

<u>Reference</u>: 2.3.1.4.8(b)

<u>Test Parameters</u>:
Loading - Axial
Frequency -
Temperature - RT
Atmosphere - Air

<u>No. of Heat/Lots</u>: 2

<u>Equivalent Stress Equation</u>:
Log N_f = 9.61-3.04 log (S_{eq}-10.0)
$S_{eq} = S_{max} (1\text{-}R)^{0.52}$
Standard Error of Estimate = 0.28
Standard Deviation in Life = 0.81
R^2 = 88%

<u>Sample Size</u> = 48

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

Table 2.4.1.0(c). Design Mechanical and Physical Properties of 5Cr-Mo-V Aircraft Steel Bar and Forging

Specification	AMS 6487 and AMS 6488		
Form	Bars and forgings		
Condition	Quenched and tempered		
Cross-sectional area, in.^{2}	a,b		
Basis	S[c]	S[c]	S[c]
Mechanical Properties:			
F_{tu}, ksi:			
L	...	260[a]	...
T	240	260[b]	280
F_{ty}, ksi:			
L	...	215[a]	...
T	200	215[b]	240
F_{cy}, ksi:			
L	...	...	...
T	220	234	260
F_{su}, ksi	144	156	168
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	400	435	465
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	315	333	365
e, percent:			
L	9	8[a]	7
T	...	...	...
RA, percent:			
L	...	30[a]	...
T	...	6[b]	...
E, 10^3 ksi	30.0		
E_c, 10^3 ksi	30.0		
G, 10^3 ksi	11.0		
μ	0.36		
Physical Properties:			
ω, lb/in.^{3}	0.281		
C, Btu/(lb)(°F)	0.11 (32°F)[d]		
K and α	See Figure 2.4.1.0		

a Longitudinal properties applicable to cross-sectional area ≤25 sq. in.
b Transverse properties applicable only to product sufficiently large to yield tensile specimens not less than 4.50 inches in length.
c Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.
d Calculated value.

Table 2.4.1.0(d). Design Mechanical and Physical Properties of 5Cr-Mo-V Aircraft Steel Sheet, Strip, and Plate

Specification	AMS 6437		
Form	Sheet, strip, and plate		
Condition	Quenched and tempered		
Thickness, in.	...		
Basis	S[a]	S[a]	S[a]
Mechanical Properties:			
F_{tu}, ksi:			
L	...	...	...
LT	240	260	280
F_{ty}, ksi:			
L	...	...	...
LT	200	220	240
F_{cy}, ksi:			
L	...	...	...
LT	220	240	260
F_{su}, ksi	144	156	168
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	400	435	465
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	315	340	365
e, percent:			
L	...	...	...
LT, in 2 inches[b]	6	5	4
LT, in 1 inch	8	7	6
E, 10^3 ksi	30.0		
E_c, 10^3 ksi	30.0		
G, 10^3 ksi	11.0		
μ	0.36		
Physical Properties:			
ω, lb/in.^{3}	0.281		
C, Btu/(lb)(°F)	0.11[c] (32°F)		
K and α	See Figure 2.4.1.0		

a Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.
b For sheet thickness greater than 0.050 inch.
c Calculated value.

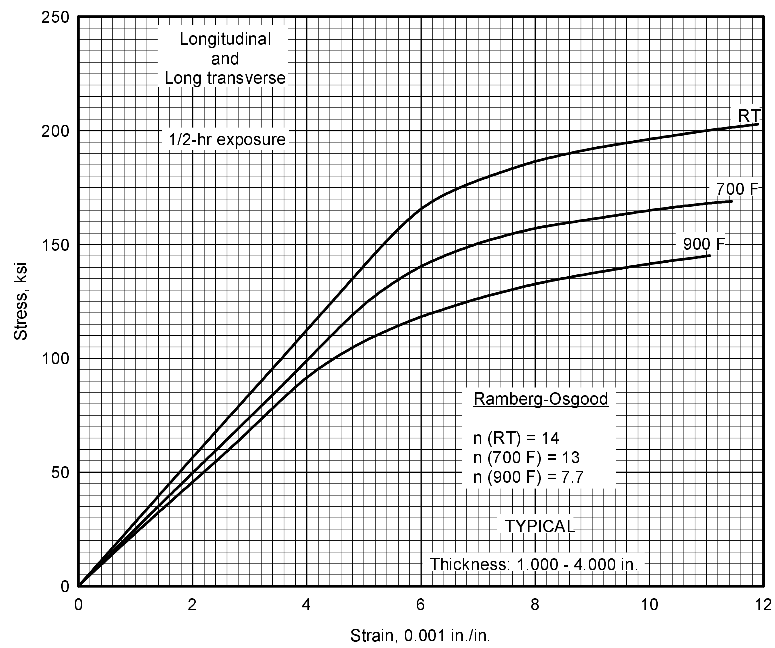

Figure 2.4.2.1.6(a). Typical tensile stress-strain curves for 9Ni-4Co-0.20C steel plate at various temperatures.

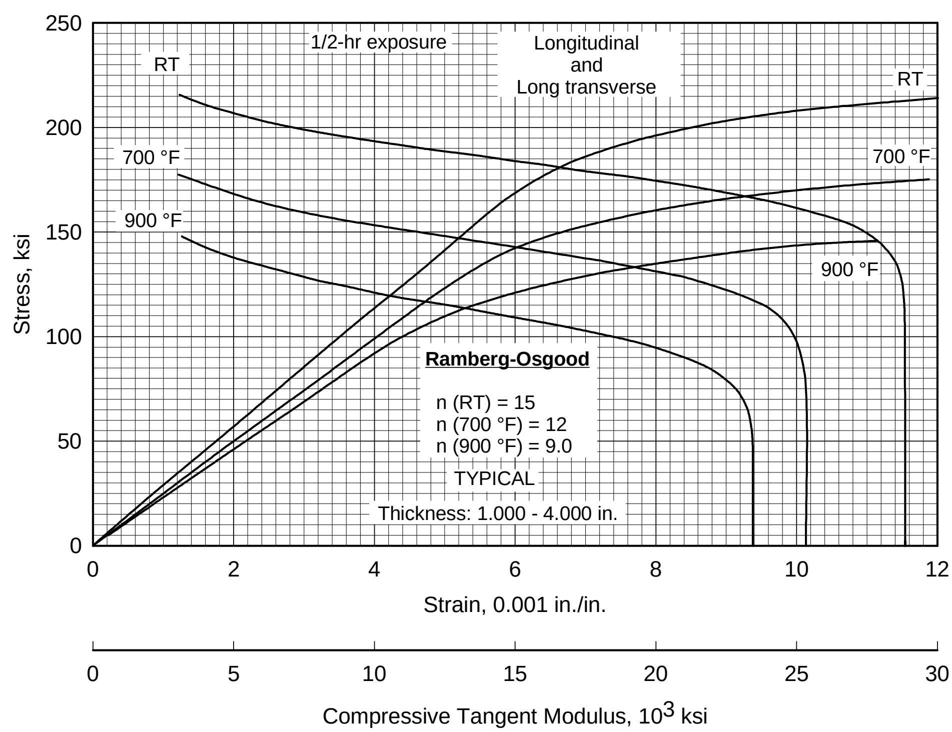

Figure 2.4.2.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 9Ni-4Co-0.20C steel plate at various temperatures.

2.4.3 9Ni-4Co-0.30C

2.4.3.0 *Comments and Properties* — The 9Ni-4Co-0.30C alloy was developed specifically to have high hardenability and good fracture toughness when heat treated to 220 to 240 ksi ultimate tensile strength. The alloy is through hardening in section sizes up to 4 inches thick. The alloy may be exposed to temperatures up to 900°F (approximately 100°F below typical tempering temperature) without microstructural changes which degrade room temperature strength. This grade must be formed and welded in the annealed condition. Preheat and post-heat of the weldment is required. The steel is produced by consumable electrode vacuum melting.

The heat treatment for this alloy consists of normalizing at 1650 ± 25°F for 1 hour per inch of cross section, cooling in air to room temperature, heating to 1550 ± 25°F for 1 hour per inch of cross section but not less than 1 hour, quenching in oil or water, subzero treating at -100°F for 1 to 2 hours, and double tempering at 975 ± 10°F (sheet, strip, and plate) or 1000 ± 10°F (bars, forgings, and tubings) for 2 hours.

Material specifications for 9Ni-4Co-0.30C steel are presented in Table 2.4.3.0(a). The room temperature mechanical and physical properties are shown in Table 2.3.4.0(b). The effect of temperature on thermal expansion is shown in Figure 2.4.3.0.

Table 2.4.3.0(a). Material Specifications for 9Ni-4Co-0.30C Steel

Specification	Form
AMS 6524[a]	Sheet, strip, and plate
AMS 6526	Bar, forging, and tubing

a Noncurrent specification.

2.4.3.1 *Heat-Treated Condition* — Effect of temperature on various mechanical properties is presented in Figures 2.4.3.1.1. through 2.4.3.1.4. Typical stress-strain and tangent-modulus curves are presented in Figures 2.4.3.1.6(a) through (d). Notched fatigue data at room temperature are illustrated in Figure 2.4.3.1.8.

Table 2.4.3.0(b). Design Mechanical and Physical Properties of 9Ni-4Co-0.30C Steel

Specification	AMS 6524[a]		AMS 6526
Form	Sheet, strip, and plate		Bar, forging, and tubing
Condition	Quenched and tempered		Quenched and tempered
Thickness, in.	≤0.249	≥0.250	≤4.000
Basis	S[b]	S[b]	S[b]
Mechanical Properties:			
F_{tu}, ksi:			
L	...	...	220
LT	220	220	...
F_{ty}, ksi:			
L	...	...	190
LT	185	190	...
F_{cy}, ksi:			
L	...	...	209
LT	...	209	...
F_{su}, ksi	...	137	137
F_{bru}[c], ksi:			
(e/D = 1.5)	...	346	346
(e/D = 2.0)	...	440	440
F_{bry}[c], ksi:			
(e/D = 1.5)	...	291	291
(e/D = 2.0)	...	322	322
e, percent:			
L	...	...	10
LT	6	10	...
RA, percent:			
L	...	...	40
LT	...	35	...
E, 10^3 ksi	28.5		
E_c, 10^3 ksi	29.8		
G, 10^3 ksi	...		
μ	...		
Physical Properties:			
ω, lb/in.^{3}	0.28		
C, Btu/(lb)(°F)	...		
K, Btu/[(hr)(ft^2)(°F)/ft]	13.3 (75°F)		
α, 10^{-6} in./in./°F	See Figure 2.4.3.0		

a Noncurrent specification.

b Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.

c Bearing values are "dry pin" values per Section 1.4.7.1.

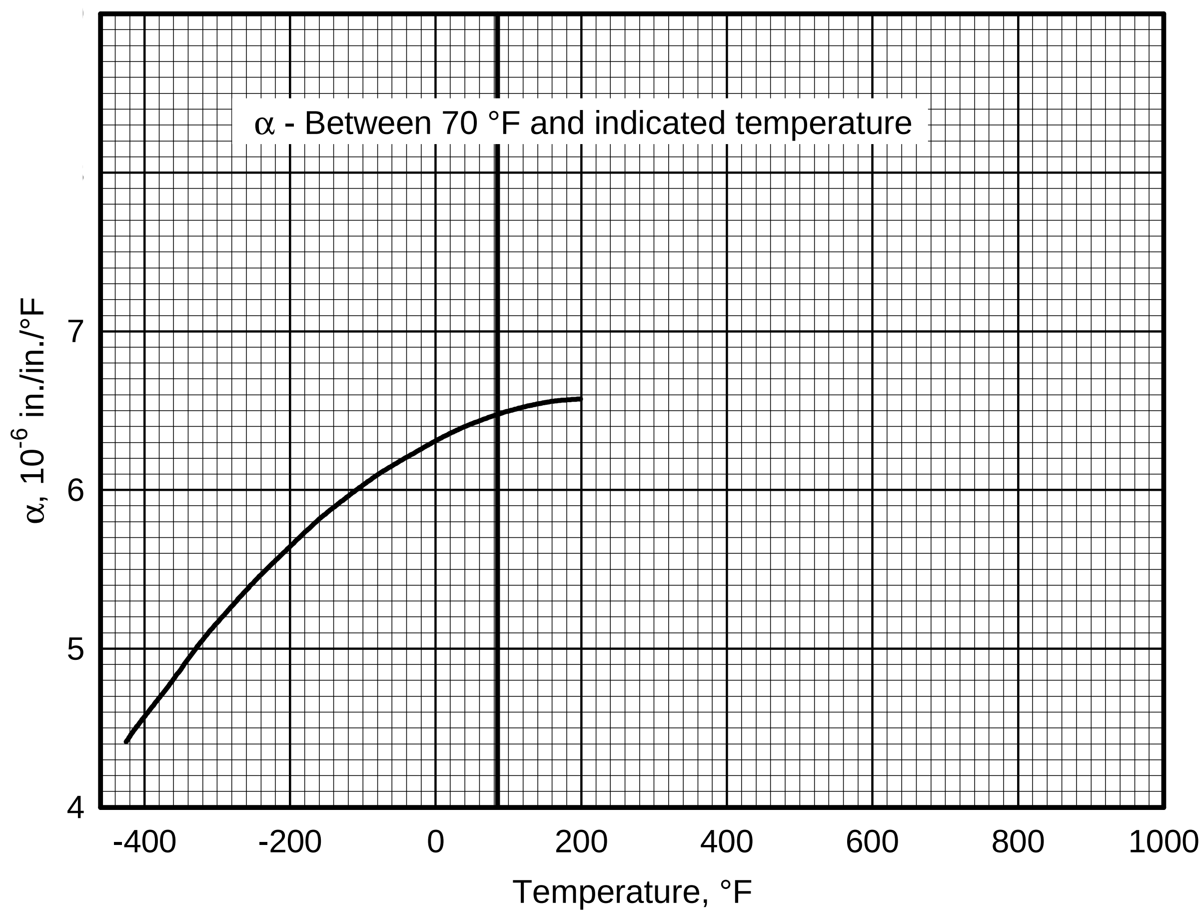

Figure 2.4.3.0. Effect of temperature on the thermal expansion of 9Ni-4Co-0.30C steel.

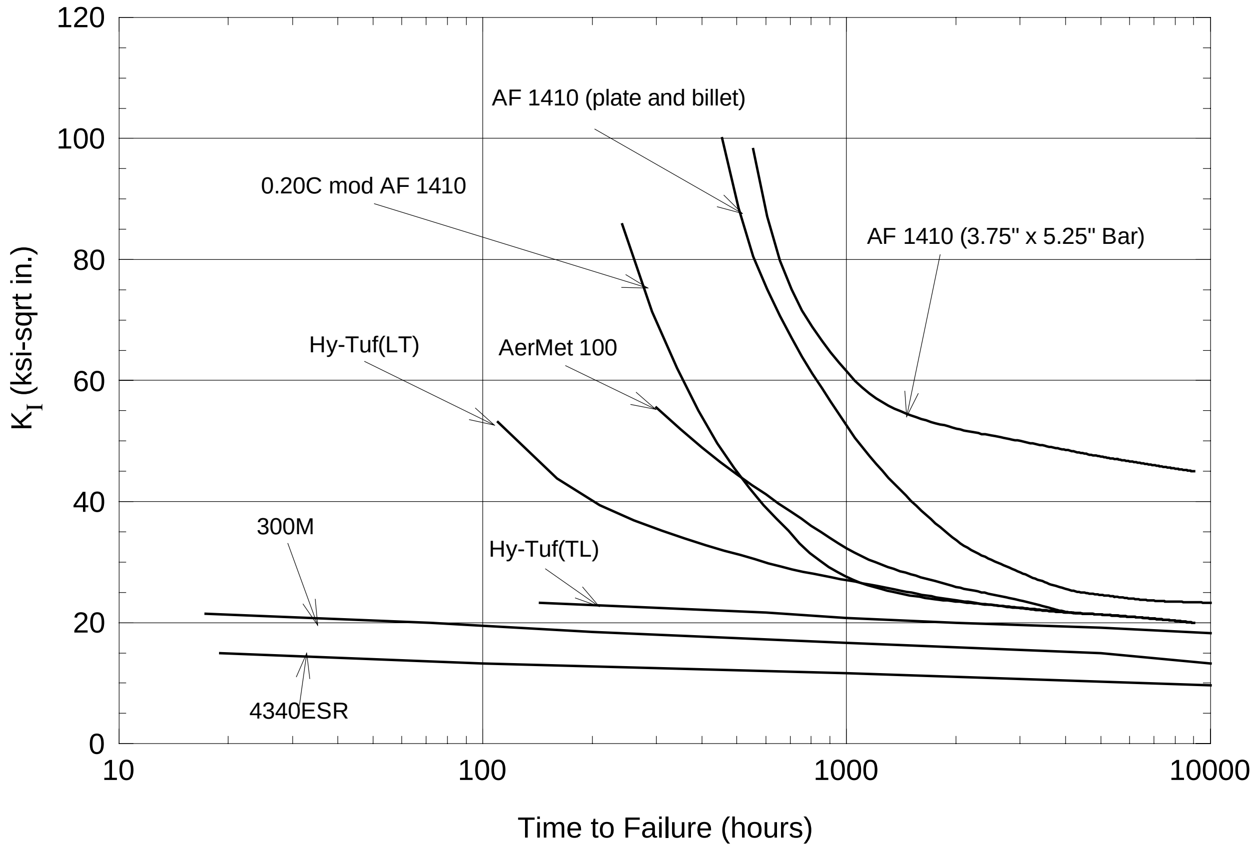

Figure 2.5.0.2(a). The relative stress corrosion cracking resistance of several high-strength steels tested in an environment of 3.5% NaCl (Reference 2.5.0.2).

2.5.1 18 Ni Maraging Steels

2.5.1.0 *Comments and Properties* — The 250 and 280 (300) maraging steels are normally supplied in the annealed condition and are heat treated to high strengths, without quenching, by aging at 900°F. The steels are characterized by high hardenability and high strength combined with good toughness. The 250 and 280 (300) designation refers to the nominal yield strengths of the two alloys. The two alloys are available in the form of sheet, plate, bar, and die forgings. Only the consumable electrode-vacuum-melted quality grades are considered in this section.

Manufacturing Considerations — The 250 and 280 grades are readily hot worked by conventional rolling and forging operations. These grades also have good cold forming characteristics in spite of the relatively high hardness in the annealed (martensitic) condition. The machinability of the 250 and 280 grades is not unlike 4330 steel at equivalent hardness. The 18 Ni maraging steels can be readily welded in either the annealed or aged conditions without preheating. Welding of aged material should be followed by aging at 900°F to strengthen the weld area.

Environmental Considerations — Although the 18 Ni maraging steels are high in alloy content, these grades are not corrosion resistant. Since the general corrosion resistance is similar to the low-alloy steels, these steels require protective coatings. The 250 grade reportedly has better resistance to stress corrosion cracking than the low-alloy steels at the same strength.

Specifications and Properties — Material specifications for these steels are shown in Table 2.5.1.0(a). The room temperature properties for material aged at 900°F are shown in Tables 2.5.1.0(b) and (c), and the effect of temperature on physical properties is shown in Figure 2.5.1.0.

Table 2.5.1.0(a). Material Specifications for 18 Ni Maraging Steels

Grade	Specification	Form
250	AMS 6520	Sheet and plate
250	AMS 6512	Bar
280 (300)	AMS 6521[a]	Sheet and plate
280 (300)	AMS 6514	Bar

a Noncurrent specification.

2.5.1.1 *Maraged Condition (aged at 900°F)* — Effect of temperature on 250 and 280 grade maraging steel is presented in Figures 2.5.1.1.1 through 2.5.1.1.4. Figures 2.5.1.1.6(a) and (b) are room and elevated temperature tensile stress-strain curves. Typical compressive stress-strain and tangent-modulus curves at room temperature are presented in Figures 2.5.1.1.6(c) and (d). Figure 2.5.1.1.6(e) is a full-range stress-strain curve at room temperature for 280 grade maraging steel.

Table 2.5.1.0(b). Design Mechanical and Physical Properties of 250 Maraging Steel

Specification	AMS 6520			AMS 6512	
Form	Sheet	Plate		Bar	
Condition	Maraged at 900°F			Maraged at 900°F	
Thickness or diameter, in.	≤0.187	0.187-0.250	>0.250	<4.000	4.000-10.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu} ksi:					
L	247	252	...	255	245
T	255	255	255	255	245
F_{ty}, ksi:					
L	238	242	...	250	240
T	245	245	245	250	240
F_{cy}, ksi:					
L	221	...	...	260	...
T	225	255	...	...	...
F_{su}, ksi	148	155	...	148	...
F_{bru}, ksi:					
(e/D = 1.5)	327	352	...	...	...
(e/D = 2.0)	444	448	...	...	...
F_{bry}, ksi:					
(e/D = 1.5)	278	324	...	...	...
(e/D = 2.0)	353	354	...	...	...
e, percent:					
L	...[a]	...[a]	...[a]	6	5
T				4	3
RA, percent:					
L	...	...	...	45	30
T	...	...	...	35	20
E, 10^3 ksi	26.5				
E_c, 10^3 ksi:					
L	28.2				
T	29.4				
G, 10^3 ksi	...				
μ	0.31				
Physical Properties:					
ω, lb/in.^{3}	0.286				
C, K, and α	See Figure 2.5.1.0				

a Elongation properties vary with thickness as follows:

≤0.090	2.5%
0.091-0.125	3.0%
0.126-0.250	4.0%
0.251-0.375	5.0%
≥0.376	6.0%

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Table 2.5.1.0(c). Design Mechanical and Physical Properties of 280 Maraging Steel

Specification	AMS 6521[a]			AMS 6514	
Form	Sheet	Plate		Bar	
Condition	Maraged at 900°F			Maraged at 900°F	
Thickness or diameter, in.	≤0.187	0.188-0.250	>0.250	<4.000	4.000-10.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu} ksi:					
L	271	276	...	280	275
T	280	280	280	280	275
F_{ty}, ksi:					
L	262	267	...	270	270
T	270	270	270	270	270
F_{cy}, ksi:					
L	244	...	...	281	...
T	248	281	...	...	...
F_{su}, ksi	163	170	...	162	...
F_{bru}, ksi:					
(e/D = 1.5)	359	386	...	...	...
(e/D = 2.0)	487	492	...	...	...
F_{bry}, ksi:					
(e/D = 1.5)	306	357	...	...	...
(e/D = 2.0)	389	390	...	...	...
e, percent:					
L	...[b]	...[b]	...[b]	5	4
T				4	2
RA, percent:					
L	...	...	...	30	25
T	...	...	...	25	20
E, 10^3 ksi	26.5				
E_c, 10^3 ksi:					
L	28.6				
T	29.6				
G, 10^3 ksi	...				
μ	0.31				
Physical Properties:					
ω, lb/in.^{3}	0.286				
C, K, and α	See Figure 2.5.1.0				

a Noncurrent specification.
b Elongation properties vary with thickness as follows:

≤0.090	2.5%
0.091-0.125	3.0%
0.126-0.250	4.0%
0.251-0.375	5.0%
≥0.376	6.0%

Table 2.5.3.0(b). Design Mechanical and Physical Properties of AerMet 100 Steel Bar

Specification	AMS 6532		AMS 6478
Form	Bar and forging		
Condition	Solution treated and aged		
Cross-sectional area, in.^{2}.	≤ 100		
Thickness or diameter, in.	≤ 10.000		
Basis	A	B	S
Mechanical Properties:			
F_{tu}, ksi:			
L	275	284	290
LT[a]	280	284	290
ST[a]	280[b]	...	290
F_{ty}, ksi:			
L	235	247	245
LT[a]	235	246	245
ST[a]	235[b]	...	245
F_{cy}, ksi:			
L	262	276	281
ST[a]	263	277	279
F_{su}, ksi	174	177	182
F_{bru}[c], ksi:			
(e/D = 1.5)	432	440	448
(e/D = 2.0)	569	579	581
F_{bry}[c], ksi:			
(e/D = 1.5)	361	380	378
(e/D = 2.0)	411	432	442
e, percent: (S-basis)			
L	10	...	10
LT[a]	8	...	8
ST[a]	8	...	8
RA, percent: (S-basis)			
L	55	...	50
LT[a]	45[d]	...	35
ST[a]	45	...	35
E, 10^3 ksi	28.0		
E_c, 10^3 ksi	28.1		
G, 10^3 ksi	...		
μ	0.305		
Physical Properties:			
ω, lb/in.^{3}	0.285		
C, K, and α	...		

a Applicable providing LT or ST dimension is ≤2.500 inches.
b S-Basis value
c Bearing values are "dry pin" values per Section 1.4.7.1.
d Rounded T_{99} value is 41%.

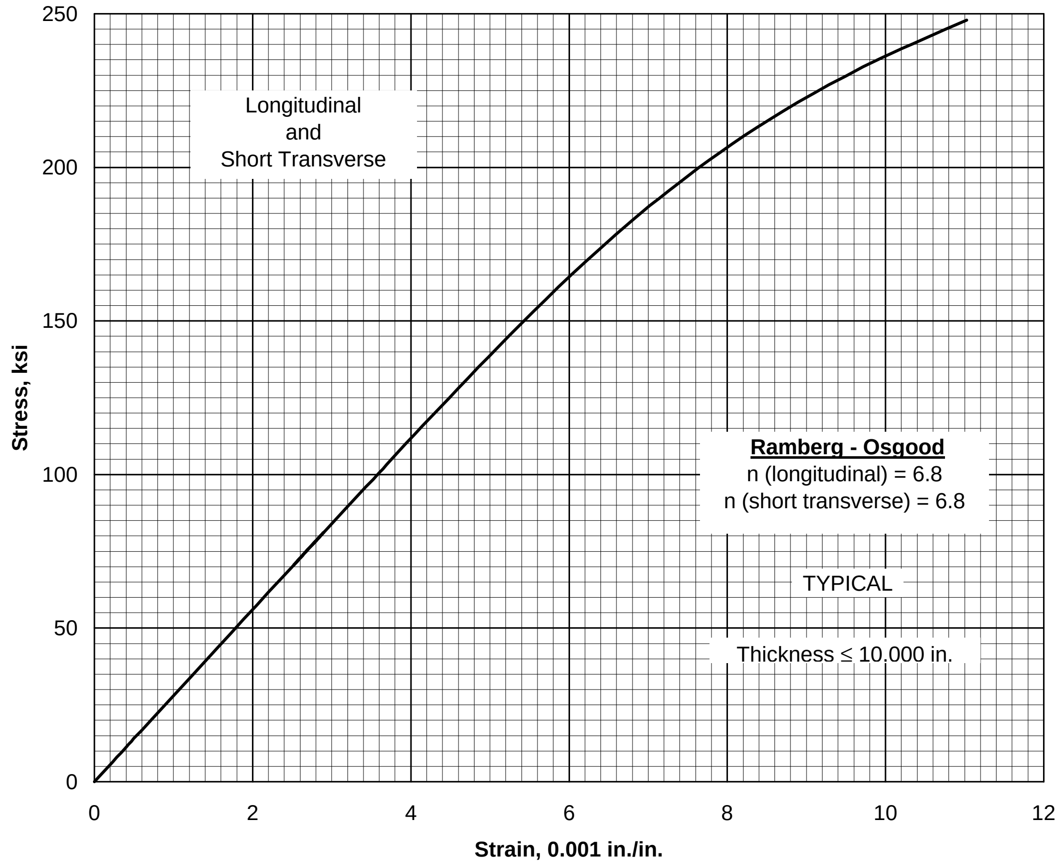

Figure 2.5.3.1.6(a). Typical tensile stress-strain curve at room temperature for AerMet 100 steel bar, heat treated to 280-300 ksi.

2.6.2 AM-355

2.6.2.0 *Comments and Properties* — AM-355, like AM-350, has high strength up to 800°F and good oxidation resistance up to 1000°F. The AM-355 alloy is generally hardened by subzero cooling and tempering (Condition SCT).

AM-355 is available in all mill products. The manufacturing considerations for AM-355 are similar to those for AM-350. Machining of AM-355 bars and forgings is best accomplished after overtempering at 1000 to 1100°F.

The differences between AM-350 and AM-355 are a result of higher carbon, lower chromium, and reduced delta ferrite in AM-355. This difference in composition makes AM-355 slightly stronger but slightly less corrosion resistant than AM-350.

Environmental Considerations — Exposure in the 600 to 800°F range for 100 hours at stress levels below the short time yield strength tends to increase room-temperature yield strength and room-temperature tensile strength slightly, with little change in elongation. Typical data are shown in Table 2.6.2.0(a).

Table 2.6.2.0(a). Effect of Elevated Temperature Exposure on Typical Tensile Properties of AM-355 Alloy in the SCT 850 Condition

Exposure temperature, °F	Exposure stress, ksi	Exposure time, hr	Room-temperature properties		
			TUS, ksi	TYS, ksi	e, %
RT	...	...	211	170	11.5
600	66	1,000	213	172	12.0
700	65	1,000	218	178	10.5
800	62	1,000	227	200	12.5
600	99	1,000	214	180	10.5
700	97	1,000	218	189	11.5
800	93	1,000	224	204	12.5

Specifications and Properties — Material specifications for AM-355 are presented in Table 2.6.2.0(b). The room temperature properties of AM-355 SCT are shown in Table 2.6.2.0(c) through (e). The physical properties of this alloy are presented in Figure 2.6.2.0.

Table 2.6.2.0(b). Material Specifications for AM-355 Stainless Steel

Specification	Form
AMS 5547	Sheet and strip
AMS 5549[a]	Plate
AMS 5743	Bar, forging, and forging stock

a Noncurrent specification.

2.6.2.1 *SCT Condition* — Elevated-temperature properties for AM-355 in the SCT (subzero cooled and tempered) condition are presented in Figures 2.6.2.1.1 through 2.6.2.1.4.

Table 2.6.2.0(c). Design Mechanical and Physical Properties of AM-355 Stainless Steel

Specification	AMS 5547		AMS 5743	
Form	Sheet and strip[a]		Bar and forging	
Condition	SCT850[b]	SCT1000	SCT850[b]	SCT1000
Thickness or diameter, in.	0.0005-0.187	0.010-0.187	...	...
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	188	...	200	170
LT	190	165	...	...
F_{ty}, ksi:				
L	162	...	165	155
LT	165	140	...	...
F_{cy}, ksi:				
L	180	...	...	...
LT	...	...	...	...
F_{su}, ksi	124	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	383	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	278	...	...	...
e, percent:				
L	...	...	10	12
LT	c	10	...	...
RA, percent:				
L	...	...	20	25
E, 10^3 ksi	29.0			
E_c, 10^3 ksi	29.0			
G, 10^3 ksi	11.0			
μ	0.32			
Physical Properties:				
ω, lb/in.^{3}	0.282			
C, K, and α	See Figure 2.6.2.0			

a Test direction longitudinal for widths less than 9 inches; transverse for widths 9 inches and over.
b Note: Condition SCT850 has been superseded by Condition SCT1000 in the applicable specifications. The tensile properties in these columns are the values previously specified for Condition SCT850.
c See Table 2.6.2.0(e).

Table 2.6.2.0(d). Design Mechanical and Physical Properties of AM-355 Stainless Steel Plate

Specification	AMS 5549[a]			
Form	Plate[b]			
Condition	SCT850[c]			SCT 1000
Thickness, in.	<0.375	0.375-1.000	>1.000	<0.187
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	188	...	...	...
LT	190	190	190	165
F_{ty}, ksi:				
L	162	...	...[d]	...
LT	165	150		140
F_{cy}, ksi:				
L	180	...	...	...
LT	...	...	...	...
F_{su}, ksi	124	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	383	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	278	...	...	...
e, percent:				
LT	10	10	10	12
E, 10^3 ksi	29.0			
E_c, 10^3 ksi	29.0			
G, 10^3 ksi	11.0			
μ	0.32			
Physical Properties:				
ω, lb/in.^{3}	0.282			
C, K, and α	See Figure 2.6.2.0			

a Noncurrent specification.
b Test direction longitudinal for widths less than 9 inches; transverse for widths 9 inches and over.
c Note: Condition SCT850 has been superseded by Condition SCT1000 in the applicable specifications. The tensile properties in these columns are the values previously specified for Condition SCT850.
d As agreed upon by purchaser and vendor.

Table 2.6.2.0(e). Minimum Elongation Values for AM-355 (SCT 850) Stainless Steel Sheet and Strip

Thickness, inches	e (LT), percent in 2 inches
0.0005 to 0.0015	2
Over 0.0015 to 0.0020	3
Over 0.0020 to 0.0050	5
Over 0.0050 to 0.0100	7
Over 0.0100 to 0.1875	8

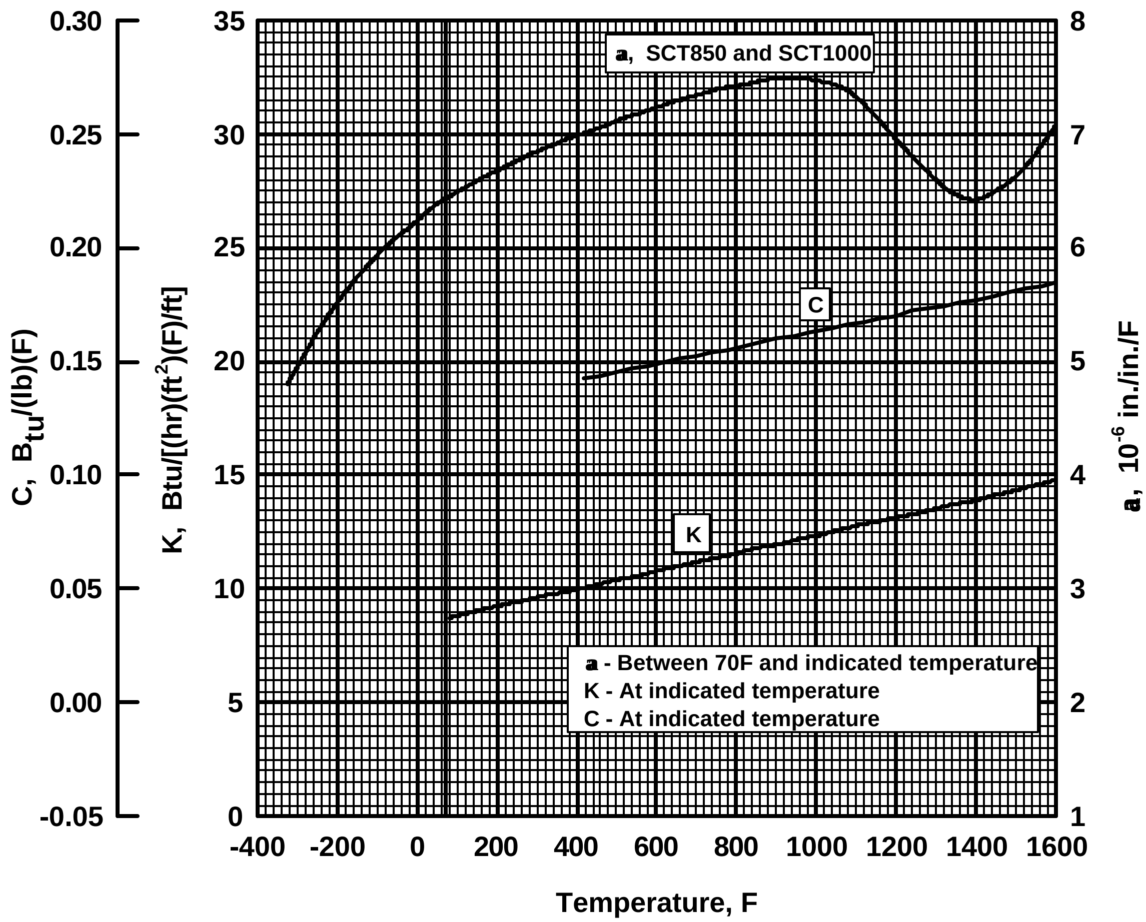

Figure 2.6.2.0. Effect of temperature on the physical properties of AM-355 stainless steel.

Table 2.6.5.0(b). Design Mechanical and Physical Properties of PH13-8Mo Stainless Steel

Specification	AMS 5629							
Form	Round, hex, square and flat bar							
Condition	H950		H1000		H1025	H1050	H1100	H1150
Thickness or diameter, in.	<9.0		<8.0		≤12.0			
Basis	A	B	A	B	S	S	S	S
Mechanical Properties:[a]								
F_{tu}, ksi:								
L	217	221	201	208	185	175	150	135
T	217	221	201	208	185	175	150	135
F_{ty}, ksi:								
L	198	205	190[b]	200	175	165	135	90
T	198	205	190[b]	200	175	165	135	90
F_{cy}, ksi:								
L	...	...	200	211	...	...	...	...
T	...	...	200	211	...	...	...	...
F_{su}, ksi	...	...	117	122	...	...	...	...
F_{bru}, ksi:								
(e/D = 1.5)	...	...	302	313	...	...	...	...
(e/D = 2.0)	...	...	402	416	...	...	...	...
F_{bry}, ksi:								
(e/D = 1.5)	...	...	263	277	...	...	...	...
(e/D = 2.0)	...	...	338	356	...	...	...	...
e, percent (S-basis):								
L	10	...	10	...	11	12	14	14
T	10	...	10	...	11	12	14	14
RA, percent (S-basis):								
L	45	...	50	...	50	50	50	50
T	35	...	40	...	45	45	50	50
E, 10^3 ksi	28.3							
E_c, 10^3 ksi	29.4							
G, 10^3 ksi	11.0							
μ	0.28							
Physical Properties:								
ω, lb/in.^{3}	0.279							
C, Btu/(lb)(°F)	0.11 (32 to 212°F) (Est.)							
K and α	See Figure 2.6.5.0							

a Design allowables were based mainly upon data from samples of material, supplied in the solution treated condition, which were aged to demonstrate response to heat treatment by suppliers.
b S-basis. Rounded T_{99} value = 193 ksi.

Table 2.6.5.0(c). Design Mechanical and Physical Properties of PH13-8Mo Stainless Steel

Specification	AMS 5629					
Form	Forging, flash welded ring, and extrusion					
Condition	H950	H1000	H1025	H1050	H1100	H1150
Thickness or diameter, in.	≤12					
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	220	205	185	175	150	135
T	220	205	185	175	150	135
F_{ty}, ksi:						
L	205	190	175	165	135	90
T	205	190	175	165	135	90
F_{cy}, ksi:						
L	...	...	...	...	...	...
T	...	...	...	...	...	...
F_{su}, ksi	...	...	...	...	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent:						
L	10	10	11	12	14	14
T	10	10	11	12	14	14
RA, percent:						
L	45	50	50	50	50	50
T	35	40	45	45	50	50
E, 10^3 ksi	28.3					
E_c 10^3 ksi	29.4					
G, 10^3 ksi	11.0					
μ	0.28					
Physical Properties:						
ω, lb/in.^{3}	0.279					
C, Btu/(lb)(°F)	0.11 (32 to 212°F) (Est.)					
K and α	See Figure 2.6.5.0					

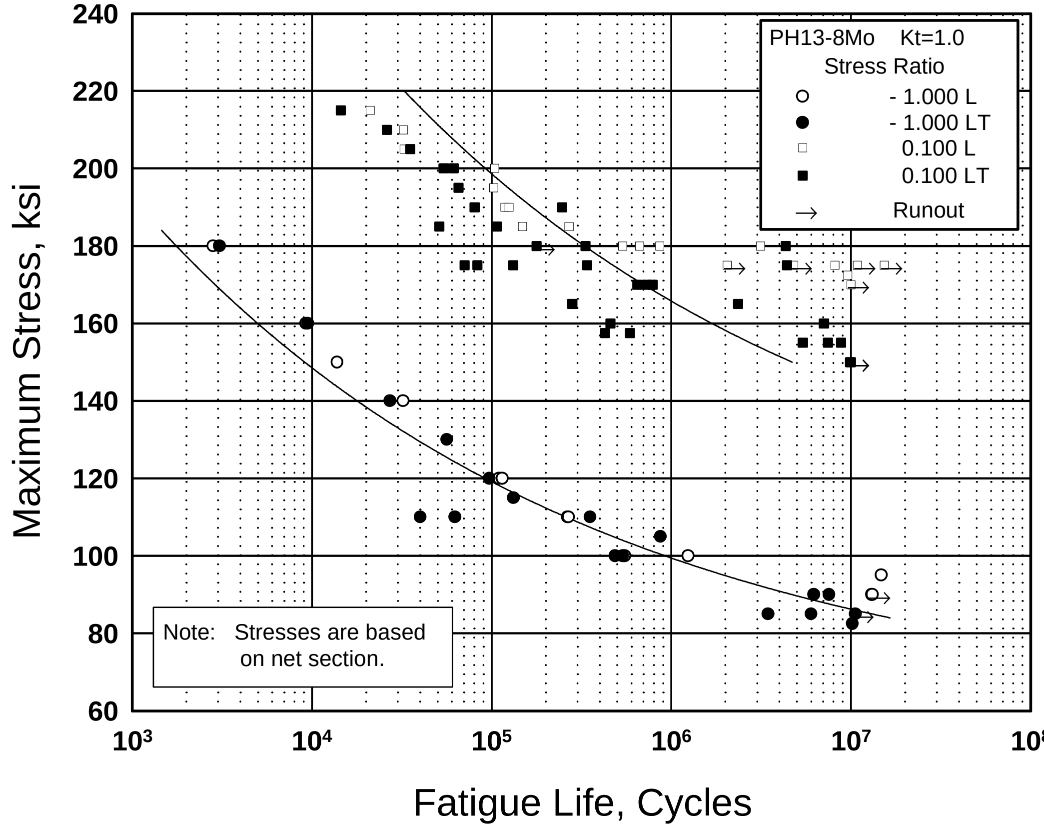

Figure 2.6.5.1.8(a). Best-fit S/N curves for unnotched PH13-8Mo (H1000) forged bar, longitudinal and transverse directions.

Correlative Information for Figure 2.6.5.1.8(a)

Product Form: Forged bar, 4 x 5 and 2 x 6 inches

Properties:

TUS, ksi	TYS, ksi	Temp., °F
205	197	RT

Specimen Details: Unnotched

Gross Diameter	Net Diameter
0.50 - 0.75	0.25

Surface Condition: Polished to RMS 10

References: 2.6.5.1.8(a), (b), (d)

Test Parameters:
Loading - Axial
Frequency - Not Specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 4

Equivalent Stress Equation:
Log N_f = 16.32 - 5.75 log (S_{eq} - 92.6)
$S_{eq} = S_{max} (1 - R)^{0.64}$
Std. Error of Estimate, Log (Life) = 0.461
Standard Deviation, Log (Life) = 0.919
R^2 = 75%

Sample Size: 86

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

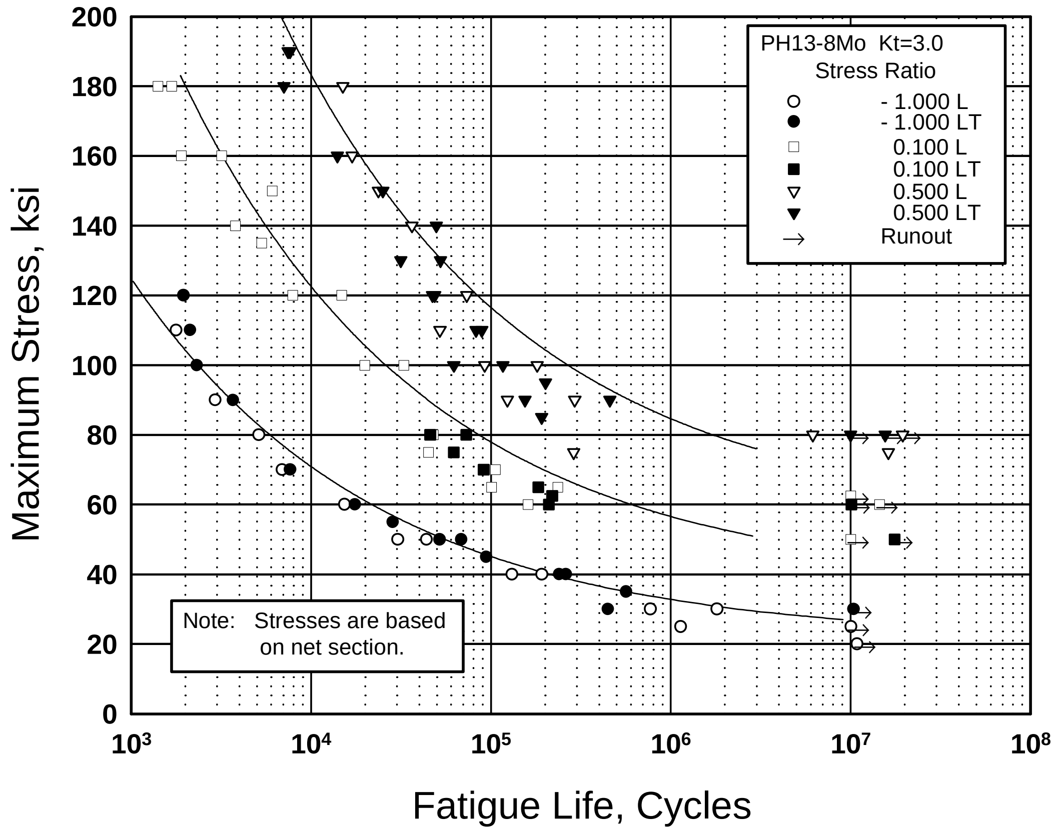

Figure 2.6.5.1.8(b). Best-fit S/N curves for notched, K_t = 3.0, PH13-8Mo (H1000) forged bar, longitudinal and long transverse directions.

Correlative Information for Figure 2.6.5.1.8(b)

Product Form: Forged bar, 4 x 5 and 2 x 6 inches

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	205	197	RT

Specimen Details: Notched, K_t = 3.0

Gross Diameter	Net Diameter	Notch Root Radius
0.750	0.252	0.013
0.500	0.250	0.013

60° flank angle

Surface Condition: Notch was polished with abrasively charged wire and rotating wire with oil and aluminum grit

References: 2.6.5.1.8(a), (b), (d)

Test Parameters:
Loading - Axial
Frequency - Not Specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 4

Equivalent Stress Equation:
Log N_f = 9.90 - 3.13 log (S_{eq} - 34.4)
$S_{eq} = S_{max} (1 - R)^{0.68}$
Std. Error of Estimate, Log (Life) = 23.1 (1/S_{eq})
Standard Deviation, Log (Life) = 1.15
R^2 = 92%

Sample Size: 104

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

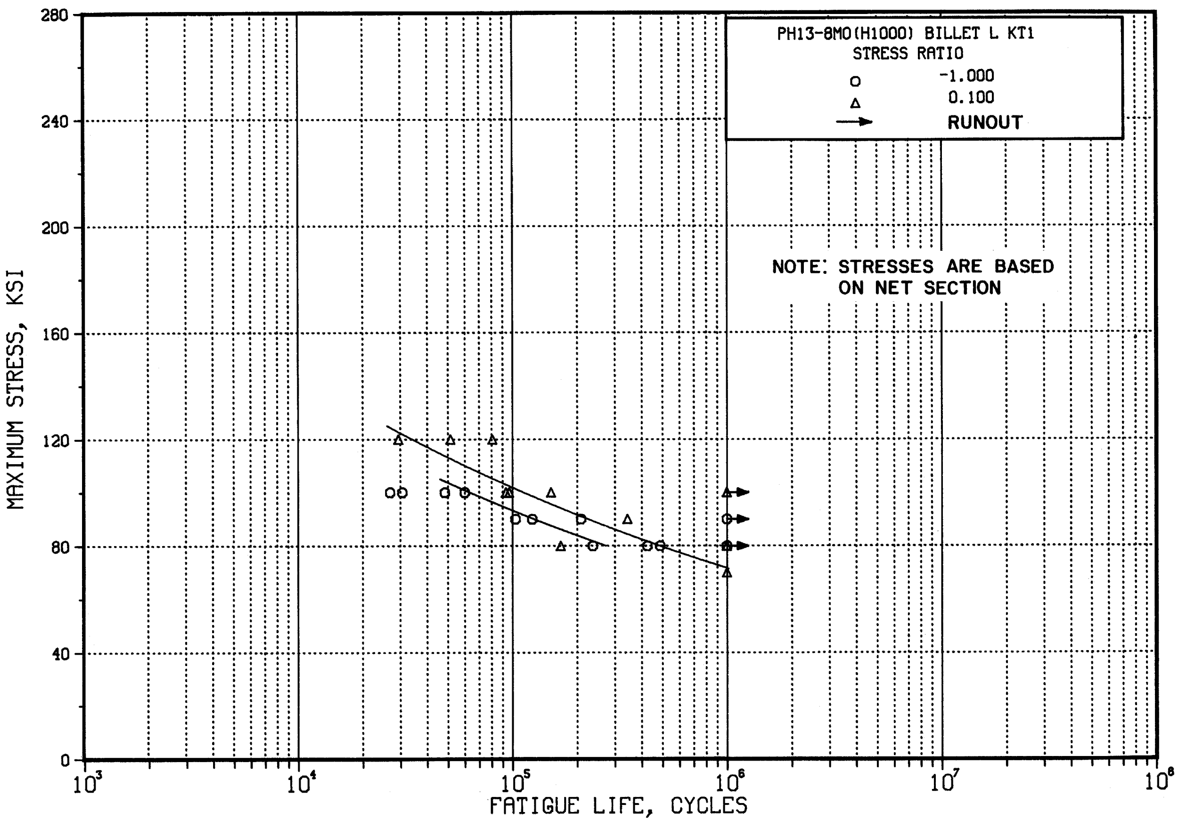

Figure 2.6.5.1.8(c). Best-fit S/N curves for unnotched PH13-8Mo (H1000) hand forging, longitudinal direction.

Correlative Information for Figure 2.6.5.1.8(c)

Product Form: Forged bar, 7 x 7 inches

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	210	204	RT

Specimen Details: Unnotched
0.500-inch gross diameter
0.250-inch net diameter

Surface Condition: Machined to RMS 63-270, solution treated and aged, grit blasted

Reference: 2.6.5.1.8(c)

Test Parameters:
Loading - Axial
Frequency - Not Specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Equivalent Stress Equation:
Log N_f = 18.12-6.54 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.11}$
Std. Error of Estimate, Log (Life) = 0.263
Standard Deviation, Log (Life) = 0.475
R^2 = 69%

Sample Size: 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

2.6.6 15-5PH

2.6.6.0 *Comments and Properties* — 15-5PH is a precipitation-hardening, martensitic stainless steel used for parts requiring corrosion resistance and high strength at temperatures up to 600°F. Alloy 15-5PH has good transverse ductility and strength in large section sizes. This material is supplied in either the annealed or overaged condition and is heat treated after fabrication. Parts should never be used in Condition A. When good fracture toughness or impact properties are required, both at or below room temperature, conditions H900 and H925 should not be used. Conditions H1025, H1075, H1100, and H1150 provide lower transition temperatures and more useful levels of fracture toughness than the H900 and H925 conditions. The H1150M condition has the best notch toughness and is recommended for cryogenic applications.

Manufacturing Considerations — 15-5PH is readily forged and welded. Forging procedures are similar to those used for 17-4PH, the forgeability of 15-5PH being superior to that of 17-4PH in critical types of upset-forging and hot-flattening operations. Machining in the solution-treated condition is done at rates similar to Type 304 and 60 percent of these rates work well for Condition H900. Highest machining rates are possible with Conditions H1150 and H1150M. Material which is hot worked must be solution-treated before hardening. A dimensional contraction of 0.0004 to 0.0006 and 0.0008 to 0.0010 in./in. will occur on hardening to the H900 and H1150 conditions, respectively.

Heat Treatment — 15-5PH must be used in the heat-treated condition and should not be placed in service in Condition A. The alloy can be heat treated to various strength levels having a wide range of properties. Consult the applicable material specification or MIL-H-6875 for specific heat treatment procedures.

Environmental Considerations — The corrosion resistance of 15-5PH is comparable to that of 17-4PH. For tensile applications where stress corrosion is a possibility, 15-5PH should be aged at the highest temperature compatible with strength requirements and at a temperature not lower than 1025°F for 4 hours minimum aging time.

Specifications and Properties — Material specifications for 15-5PH are presented in Table 2.6.6.0(a). Room-temperature mechanical and physical properties of 15-5PH are shown in Tables 2.6.6.0(b) through (d). The effect of temperature on physical properties is depicted in Figure 2.6.6.0.

Table 2.6.6.0(a). Material Specifications for 15-5PH Stainless Steel

Specification	Form
AMS 5659	Bar, forging, ring, and extrusion (CEVM)
AMS 5862	Sheet, strip, and plate (CEVM)
AMS 5400	Investment casting

2.6.6.1 *Various Heat-Treated Conditions* — Elevated temperature curves for the various mechanical properties are shown in Figures 2.6.6.1.1 and 2.6.6.1.4. Typical stress-strain and tangent-modulus curves are shown in Figures 2.6.6.1.6(a) through (c).

2.6.6.2 *H1025 Condition* — An elevated temperature curve for compressive yield strength is presented in Figure 2.6.6.2.2. Stress-strain and tangent-modulus curves are shown in Figures 2.6.6.2.6(a) and (b). Fatigue data at room temperature are illustrated in Figures 2.6.6.2.8(a) through (c).

2.6.6.3 *H1150 Condition* — An elevated temperature curve for compressive yield strength is presented in Figure 2.6.6.3.2. Compressive stress-strain and tangent-modulus curves at various temperatures are shown in Figure 2.6.6.3.6.

Table 2.6.6.0(b). Design Mechanical and Physical Properties of 15-5PH Stainless Steel Bar and Forging

Specification	AMS 5659					
Form	Bar[a]					
Condition	H900	H925	H1025	H1075	H1100	H1150
Thickness or diam., in.	≤12	≤12	≤12	≤12	≤12	≤12
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	190	170	155	145	140	135
T	190	170	155	145	140	135
F_{ty}, ksi:						
L	170	155	145	125	115	105
T	170	155	145	125	115	105
F_{cy}, ksi:						
L	...	...	143	...	...	99
T	...	...	143	...	...	99
F_{su}, ksi	...	...	97	...	...	85
F_{bru}[b], ksi:						
(e/D = 1.5)	...	...	263	...	...	230
(e/D = 2.0)	...	...	332	...	...	293
F_{bry}[b], ksi:						
(e/D = 1.5)	...	...	211	...	...	166
(e/D = 2.0)	...	...	250	...	...	201
e, percent:						
L	10	10	12	13	14	16
T	6	7	8	9	10	11
RA, percent:						
L	35	38	45	45	45	50
T	20	25	32	33	34	35
E, 10^3 ksi	28.5					
E_c, 10^3 ksi	29.2					
G, 10^3 ksi	11.2					
μ	0.27					
Physical Properties:						
ω, lb/in.^{3}	0.283					
C, Btu/(lb)(°F)	...					
K and α	See Figure 2.6.6.0					

a Forging, ring, and extrusion product forms are also covered by AMS 5659.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 2.6.6.0(c). Design Mechanical and Physical Properties of 15-5PH Stainless Steel Plate

Specification	AMS 5862			
Form	Plate			
Condition	H1025[a]			
Thickness, in.	0.187-0.625	0.626-2.000	2.001-3.000	3.001-4.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	154	154	154	...
LT	155	155	155	155
F_{ty}, ksi:				
L	143	143	143	...
LT	145	145	145	145
F_{cy}, ksi:				
L	150	150	150	...
LT	152	149	146	...
F_{su}, ksi	97	97	96	...
F_{bru}[b], ksi:				
(e/D = 1.5)	257	257	257	...
(e/D = 2.0)	331	331	331	...
F_{bry}[b], ksi:				
(e/D = 1.5)	211	211	211	...
(e/D = 2.0)	246	246	246	...
e, percent:				
LT	8	12	12	12
RA, percent:				
LT	35	40	40	40
E, 10^3 ksi	28.5			
E_c, 10^3 ksi	29.2			
G, 10^3 ksi	11.2			
μ	0.27			
Physical Properties:				
ω, lb/in.^{3}	0.283			
C, Btu/(lb)(°F)	...			
K and α	See Figure 2.6.6.0			

a The H900, H925, H1075, H1100, and H1150 conditions are included in AMS 5862.
b Bearing values are "dry pin" values per Section 1.4.7.1.

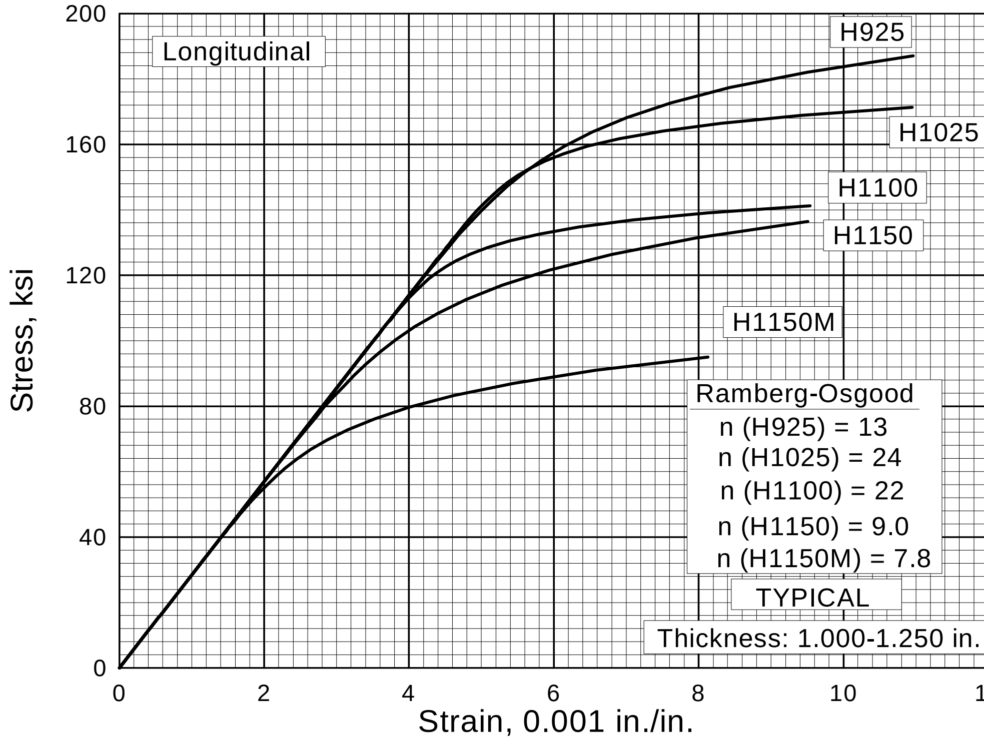

Figure 2.6.6.1.6(a). Typical tensile stress-strain curves at room temperature for various heat-treated conditions of 15-5PH stainless steel bar.

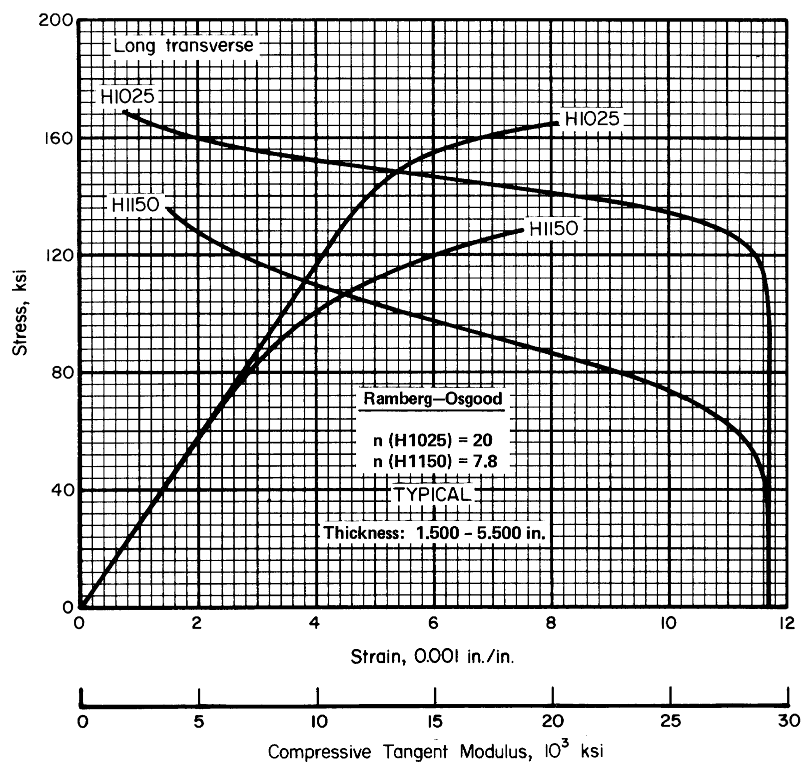

Figure 2.6.6.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for various heat-treated conditions of 15-5PH stainless steel bar.

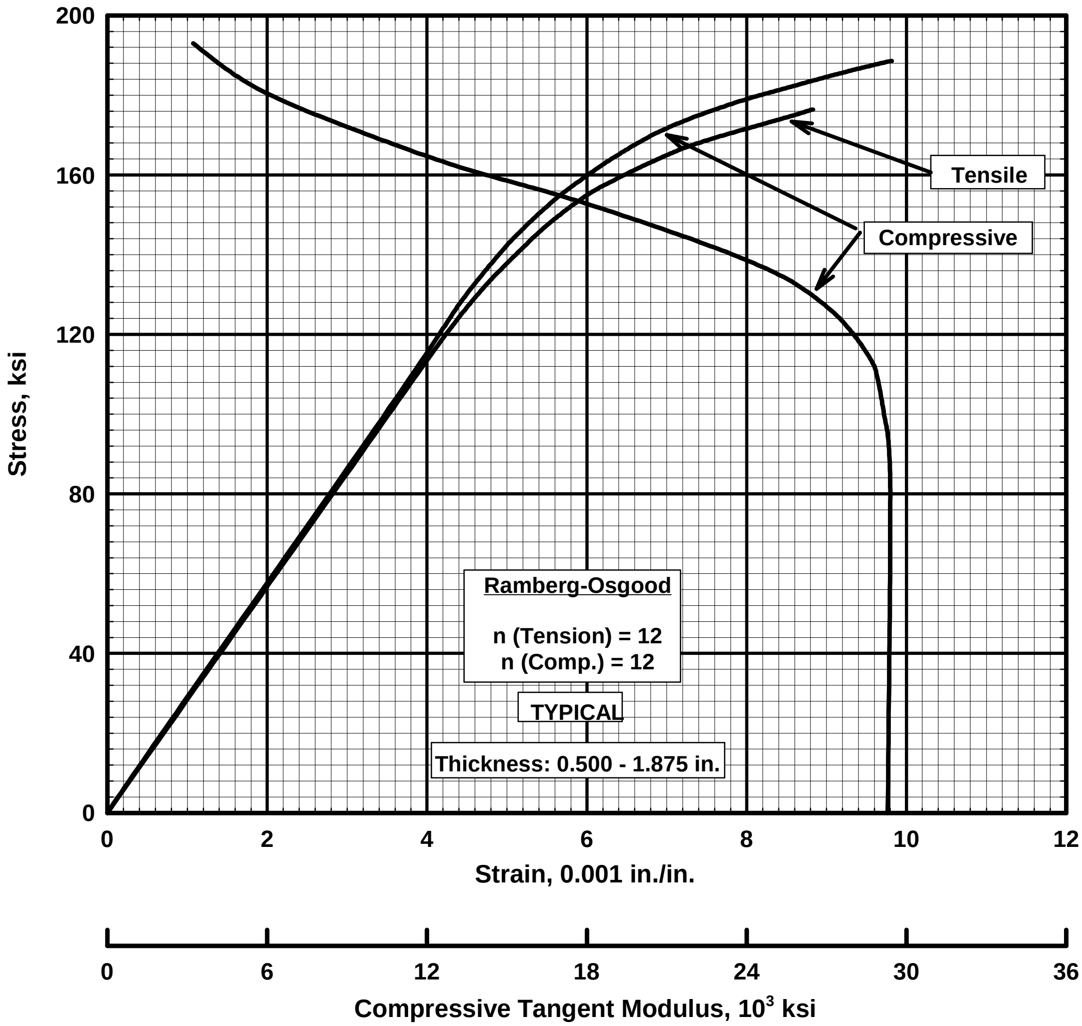

Figure 2.6.6.1.6(c). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 15-5PH (H935) stainless steel casting.

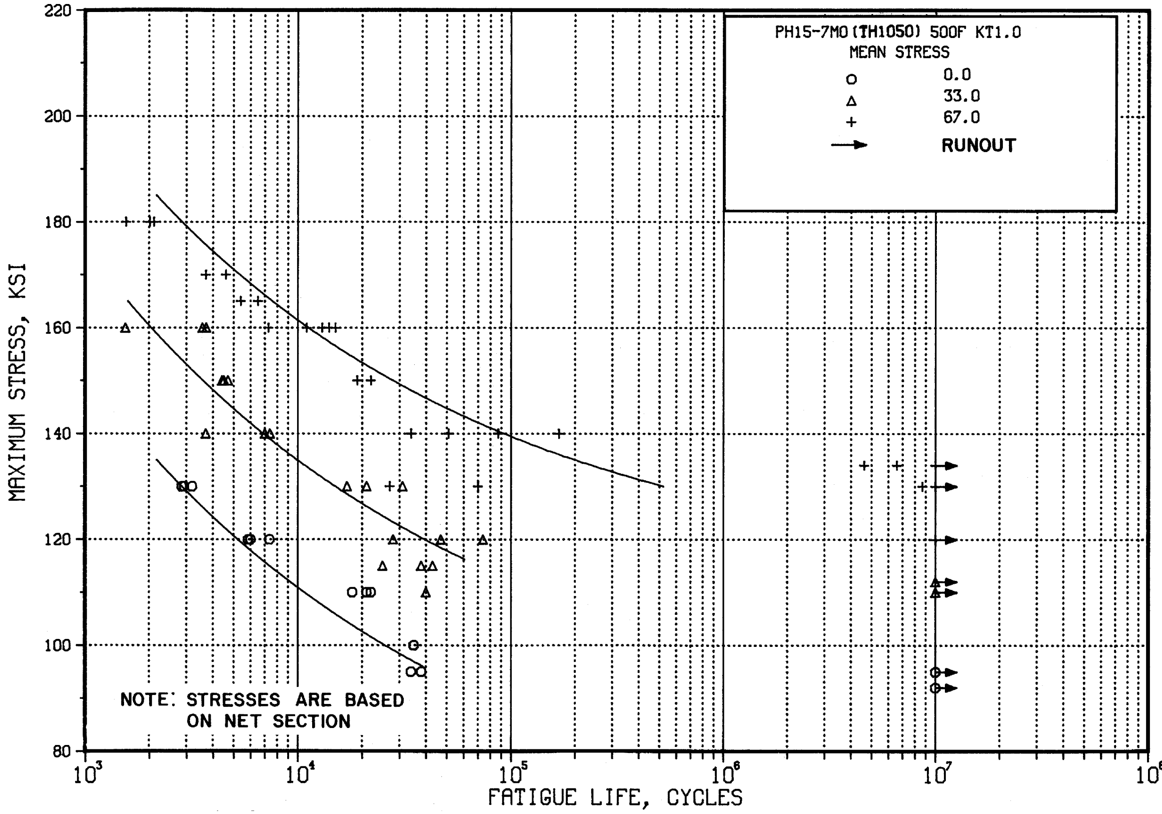

Figure 2.6.7.1.8(c). Best-fit S/N curves for unnotched PH15-7Mo (TH1050) sheet at 500EF, longitudinal direction.

Correlative Information for Figure 2.6.7.1.8(c)

Product Form: Sheet, 0.025-inch

Properties:	TUS, ksi	TYS, ksi	Temp,EF
	201	196	RT
	179	173	500

Specimen Details: Unnotched
2.0-inch gross width
0.75-inch net width

Surface Condition: Machined in longitudinal direction, edges polished with 320 grit emery paper

Reference: 2.6.7.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 24 and 1800 cpm
Temperature - 500EF
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 11.71-4.00 log (S_{eq}-96)
$S_{eq} = S_{max}\ (1\text{-}R)^{0.70}$
Std. Error of Estimate, Log (Life) = 0.44
Standard Deviation, Log (Life) = 0.79
R^2 = 69%

Sample Size: 55

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

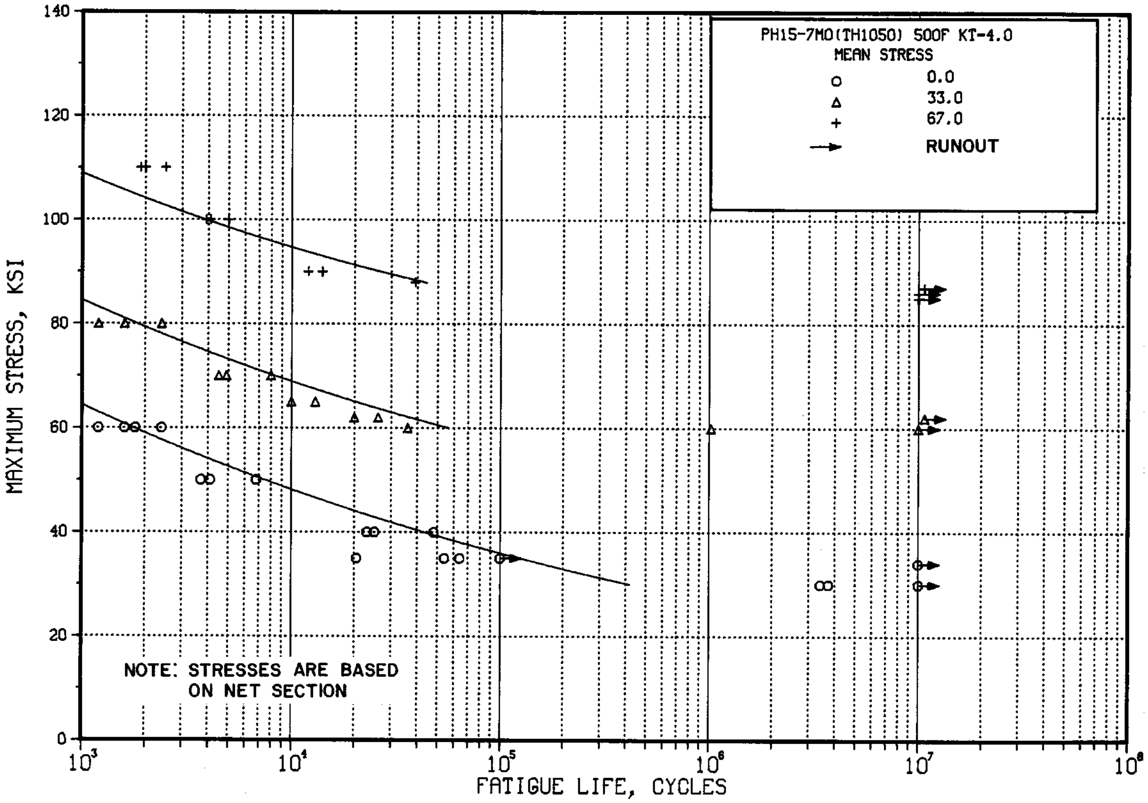

Figure 2.6.7.1.8(d). Best-fit S/N curves for notched, K_t = 4.0, PH15-7Mo (TH1050) sheet at 500°F, longitudinal direction.

Correlative Information for Figure 2.6.7.1.8(d)

Product Form: Sheet, 0.025-inch

Properties:

TUS, ksi	TYS, ksi	Temp, °F
201	196	RT
179	173	500

Specimen Details: Edge Notched, K_t = 4.0
2.25-inch gross width
1.50-inch net width
0.058-inch notch radius
0° flank angle, ω

Surface Condition: Drilled holes near edges and slots milled from edge, corners of notch were beveled with rubber abrasive

Reference: 2.6.7.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 24 and 1800 cpm
Temperature - 500°F
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 18.60-7.92 log (S_{eq})
$S_{eq} = S_{max}\,(1\text{-}R)^{0.55}$
Standard Error of Estimate = 0.41
Standard Deviation in Life = 0.86
R^2 = 77%

Sample Size: 37

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

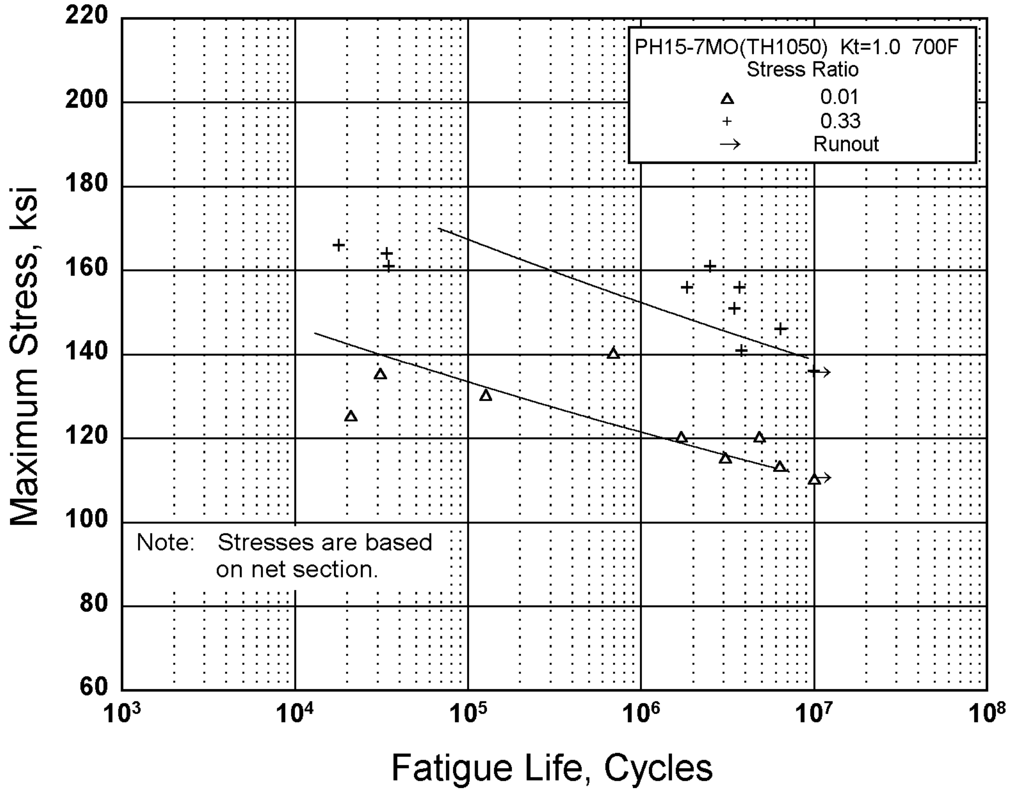

Figure 2.6.7.1.8(e). Best-fit S/N curves for PH15-7Mo (TH1050) sheet at 700EF, transverse direction.

Correlative Information for Figure 2.6.7.1.8(e)

Product Form: Sheet, 0.050-inch

Properties:	TUS, ksi	TYS, ksi	Temp,EF
	175	161	700 (LT)

Specimen Details: Unnotched
2.0-inch gross width
0.375-inch net width

Surface Condition: Polished in longitudinal direction with wet 600 grit silicon carbide paper

Reference: 2.6.7.1.8(c)

Test Parameters:
Loading - Axial
Frequency - 1200 cpm
Temperature - 700EF
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 56.92-24.46 log (S_{eq})
$S_{eq} = S_{max}$ $(1\text{-}R)^{0.58}$
Std. Error of Estimate, Log (Life) = 0.77
Standard Deviation, Log (Life) = 0.99
R^2 = 39%

Sample Size: 17

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

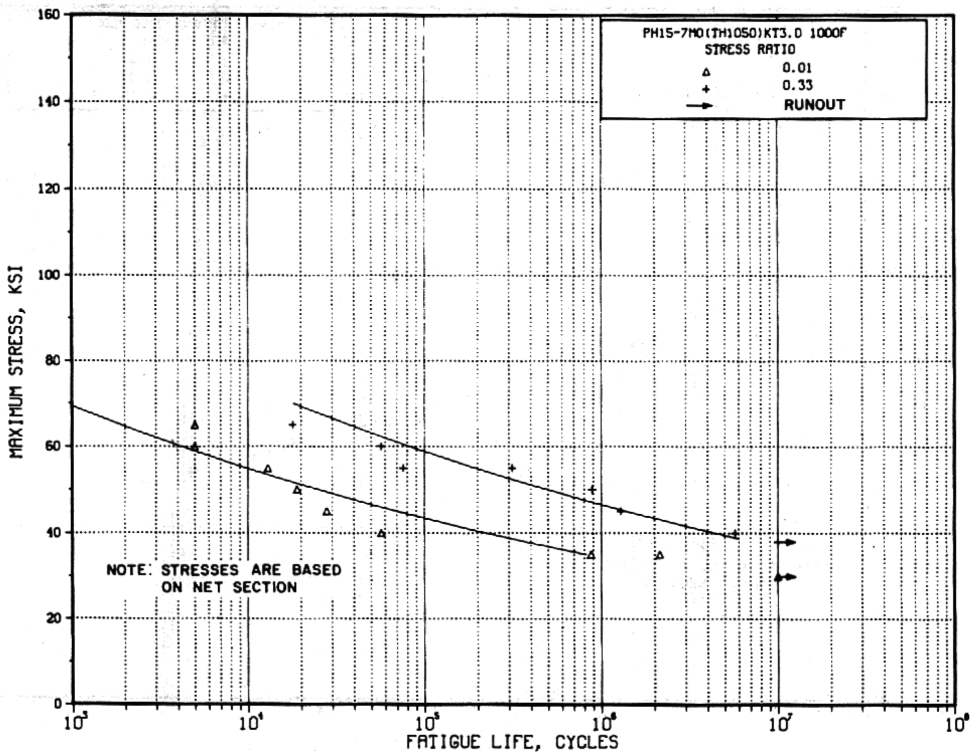

Figure 2.6.7.1.8(f). Best-fit S/N curves for notched, K_t = 3.0, PH15-7Mo (TH1050) sheet at 1000EF, transverse direction.

<u>Correlative Information for Figure 2.6.7.1.8(f)</u>

<u>Product Form:</u> Sheet, 0.050-inch

<u>Properties:</u>

TUS, ksi	TYS, ksi	Temp,EF
107	92	1000 (LT)

<u>Specimen Details:</u> Edge Notched, K_t = 3.0
0.535-inch gross width
0.375-inch net width
0.021-inch notch radius
60E flank angle, ω

<u>Surface Condition:</u> Polished longitudinally

<u>Reference:</u> 2.6.7.1.8(c)

<u>Test Parameters</u>:
Loading - Axial
Frequency - 1200 cpm
Temperature - 1000EF
Environment - Air

<u>No. of Heats/Lots:</u> Not specified

<u>Equivalent Stress Equation</u>:
Log N_f = 21.00-9.80 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.78}$
Std. Error of Estimate, Log (Life) = 0.33
Standard Deviation, Log (Life) = 0.99
R^2 = 89%

<u>Sample Size:</u> 16

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

Table 2.6.8.0(e). Design Mechanical and Physical Properties of 17-4PH Stainless Steel Bar

Specification	AMS 5643										
Form	Bar										
Condition	H900		H925		H1025	H1075		H1100	H1150		H1150M[a]
Thickness or diameter, in.	<8.000										
Basis	A	B	A	B	S	A	B	S	A	B	S[a]
Mechanical Properties:[b]											
F_{tu}, ksi:											
L	190	195	170	178	155	143	150	140	125	134	115
T	...	...	...	...	...	...	...	...	...	...	...
F_{ty}, ksi:											
L	170	175	155[c]	167	145	125[d]	143	115	100	115	75
T	...	...	...	...	...	...	...	...	...	...	...
F_{cy}, ksi:											
L	170	175	...	...	139	...	...	...	90	104	...
T	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	123	126	...	...	95	...	...	...	79	85	...
F_{bru}, ksi:											
(e/D = 1.5)	313	322	...	...	263[e]	...	...	...	213[e]	228[e]	...
(e/D = 2.0)	380	390	...	...	332[e]	...	...	...	270[e]	289[e]	...
F_{bry}, ksi:											
(e/D = 1.5)	255	262	...	...	211[e]	...	...	...	152[e]	175[e]	...
(e/D = 2.0)	280	288	...	...	250[e]	...	...	...	181[e]	208[e]	...
e, percent (S-basis):											
L	10	...	10	...	12	13	...	14	16	...	18
E, 10^3 ksi	28.5										
E_c, 10^3 ksi	30.0										
G, 10^3 ksi	11.2										
μ	0.27										
Physical Properties:											
ω, lb/in.^{3}	0.282 (H900), 0.283 (H1075), 0.284 (H1150)										
C, K, and α	See Figure 2.6.8.0										

a Not covered by AMS 5643. S values are producer's guaranteed minimum tensile properties.
b Design allowables were based upon data from samples of material, supplied in the solution treated condition, which were aged to demonstrate response to heat treatment by suppliers.
c S-basis. Rounded T_{99} value = 157 ksi.
d S-basis. Rounded T_{99} value = 136 ksi.
e Bearing values are "dry pin" values per Section 1.4.7.1.

Table 2.6.8.0(f). Design Mechanical and Physical Properties of 17-4PH Stainless Steel Investment Casting

Specification	AMS 5344	AMS 5343	AMS 5342
Form	Investment Casting		
Condition	[a]	H1000[b]	H1100[c]
Location within casting	Any area		
Basis	S	S	S
Mechanical Properties[d]:			
F_{tu}, ksi	180	150	130
F_{ty}, ksi	160	130	120
F_{cy}, ksi	...	132	...
F_{su}, ksi	...	98	...
F_{bru}[e], ksi:			
(e/D = 1.5)	...	254	...
(e/D = 2.0)	...	329	...
F_{bry}[e], ksi:			
(e/D = 1.5)	...	189	...
(e/D = 2.0)	...	222	...
e, percent	4	4	6
RA, percent	12	12	15
E, 10^3 ksi	28.5		
E_c, 10^3 ksi	30.0		
G, 10^3 ksi	12.7		
μ	0.27		
Physical Properties:			
ω, lb/in.^{3}	0.282 (H900)		
C, K, and α	See Figure 2.6.8.0		

a Aged at 900 to 925°F for 90 minutes.
b Aged at 985 to 1015°F for 90 minutes.
c Aged at 1085 to 1115°F for 90 minutes.
d Properties apply only when drawing specifies that conformance to tensile property requirements shall be determined from specimens cut from casting or integrally cast specimens.
e Bearing values are “dry pin” values per Section 1.4.7.1.

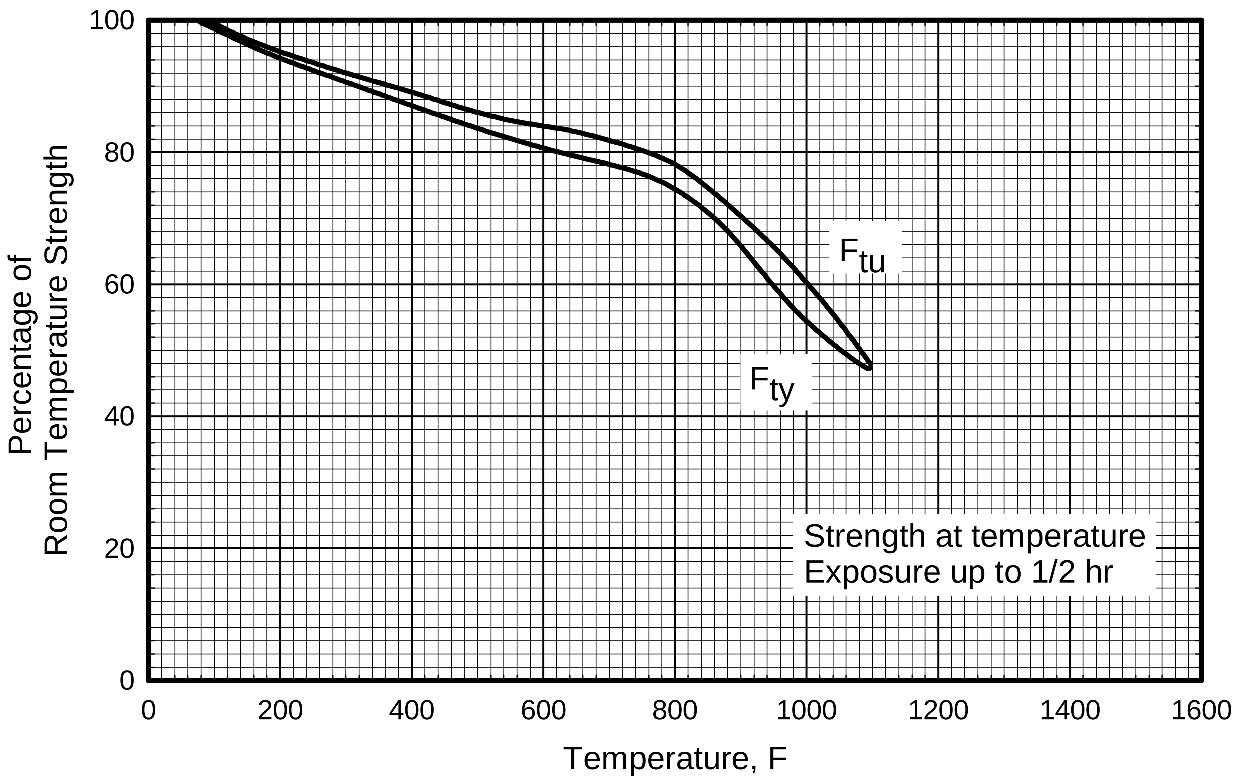

Figure 2.6.8.2.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 17-4PH (H900, H925, H1025, and H1075) stainless steel bar.

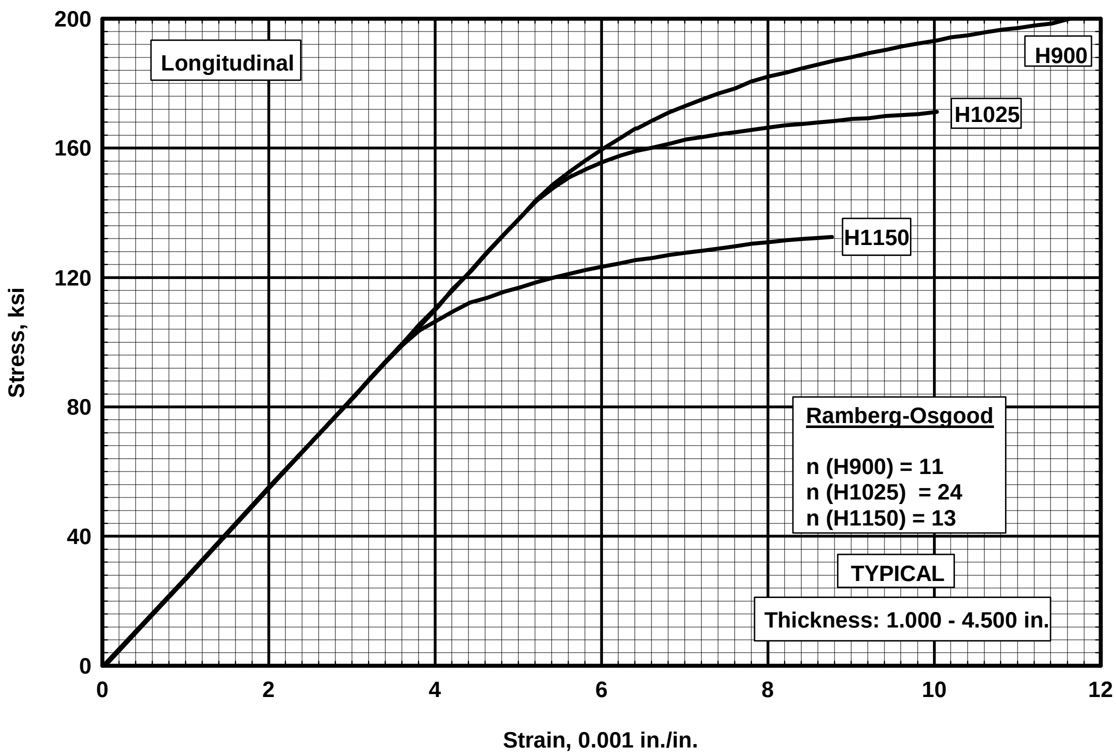

Figure 2.6.8.2.6(a). Typical tensile stress-strain curves at room temperature for various heat treated conditions of 17-4PH stainless steel bar.

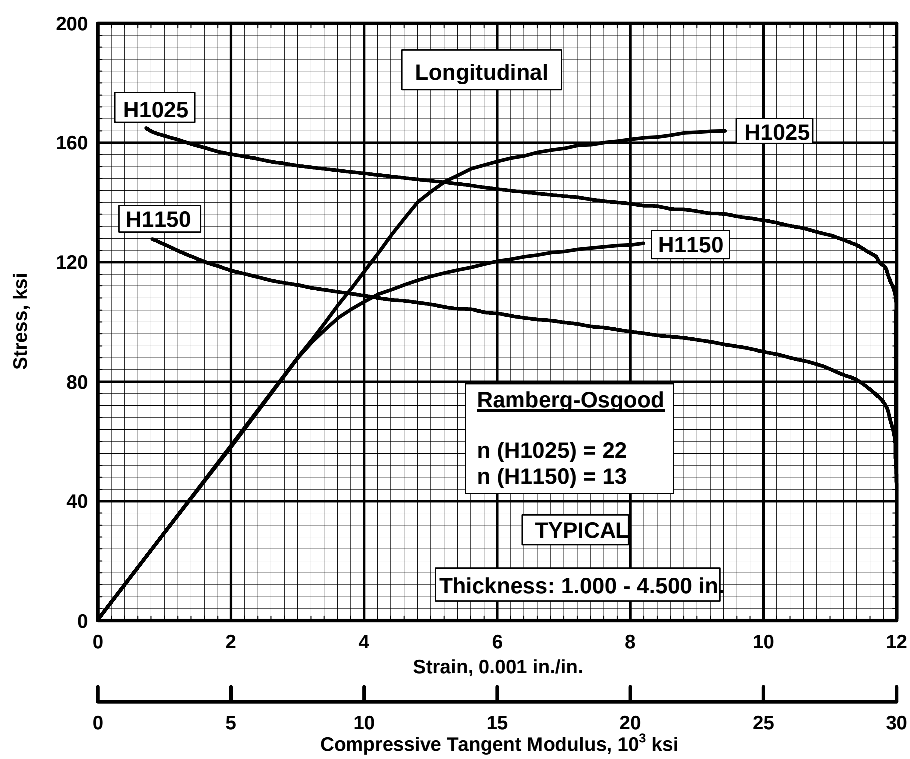

Figure 2.6.8.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for various heat treated conditions of 17-4PH stainless steel bar.

Table 2.7.0.1. Characteristics of Some AISI 300 Series Stainless Steels

AISI	Characteristics
301	High work-hardening rate; applications requiring high strength and ductility.
302	Higher carbon modification of Type 304 for higher strength on cold rolling.
303	Free machining sulfur modification of Type 302.
303Se	Free machining selenium modification of Type 302.
304	General purpose austenitic grade for enhanced corrosion resistance.
304L	Low-carbon modification of Type 304 for welding applications.
305	Low work-hardening rate; spin forming and severe spin drawing operations.
309	High-temperature strength and oxidation resistance.
309S	Low-carbon modification of Type 309 for welded construction.
310	High-temperature strength and oxidation resistance greater than Type 309.
310S	Low-carbon modification of Type 310 for welded construction.
314	Increased oxidation resistance over Type 310.
316	Mo added to improve corrosion resistance in reducing environments; improved creep resistance over Type 302.
316L	Low-carbon modification of Type 316 for welded construction.
317	Increased Mo to improve corrosion resistance over Type 316 in reducing media.
321	Titanium stabilized for service in 800 to 1600°F range and to minimize carbide precipitation when welding for resistance to intergranular corrosion.
347	Columbium stabilized for service in 800 to 1600°F range and to minimize carbide precipitation when welding for resistance to intergranular corrosion.

slightly higher in alloy content, as the material to be welded. Special fluxes designed for use with stainless steels should be employed, except in atomic hydrogen or inert-gas-shielded arc welding. Spot and roll seam welding also are used to a considerable extent.

Brazing — Special techniques have been developed for silver-soldering and brazing these steels. Solders and fluxes especially designed should be used, surfaces must be thoroughly cleaned, and close control of temperature must be followed.

2.7.0.3 *Environmental Considerations* — The austenitic stainless steels have excellent oxidation resistance at high temperatures, and their elevated-temperature service is usually limited by strength criteria. They also possess unusually good resistance to corrosion by most media. Prolonged exposure of the nonstabilized grades to temperatures between 700 and 1650°F makes them susceptible to intergranular corrosion.

2.7.1 AISI 301

2.7.1.0 ***Comments and Properties*** — Of the austenitic stainless steels, AISI 301 is the one most frequently used at high-strength levels in aircraft, mainly because of its greater work-hardening characteristics.

Type 301 is strengthened by cold working. If cold-worked Type 301 is subjected to temperatures above 900°F, its room-temperature strength is reduced.

Type 301 should not be used for extended periods at temperatures of 750 to 1650°F and should not be cooled slowly from higher temperatures through this range.

Material specifications for AISI 301 stainless steel are presented in Table 2.7.1.0(a). The room-temperature mechanical and physical properties for AISI 301 stainless steel are presented in Tables 2.7.1.0(b) and (c). The physical properties of this alloy at room and elevated temperatures are presented in Figure 2.7.1.0. Specifications for related 300 series alloys for which the properties are applicable are footnoted in Table 2.7.1.0(b).

Table 2.7.1.0(a). Material Specifications for AISI 301 Stainless Steel

Specification	Form
AMS 5517	Sheet and strip
AMS 5518	Sheet and strip
AMS 5519	Sheet and strip
AMS 5901	Plate, sheet, and strip
AMS 5902	Sheet and strip

2.7.1.1 ***Annealed Condition*** — Elevated temperature curves for tensile yield and ultimate strengths are presented in Figures 2.7.1.1.1(a) and (b).

2.7.1.2 ***¼ Hard Condition*** — Typical room-temperature stress-strain and tangent-modulus curves are presented in Figures 2.7.1.2.6(a) and (b).

2.7.1.3 ***½ Hard Condition*** — Elevated temperature curves for various mechanical properties are presented in Figures 2.7.1.3.1 through 2.7.1.3.4. Typical stress-strain and tangent-modulus curves are presented in Figures 2.7.1.3.6(a) and (b).

2.7.1.4 ***¾ Hard Condition*** — Typical room-temperature stress-strain and tangent-modulus curves are presented in Figures 2.7.1.4.6(a) and (b).

2.7.1.5 ***Full-Hard Condition*** — The full-hard condition is a standard AISI temper and is developed by cold rolling 40 to 50 percent. Elevated temperature curves for various mechanical properties are presented in Figure 2.7.1.5.1 through 2.7.1.5.4. Tensile and compressive stress-strain as well as tangent-modulus curves at room temperature and several elevated temperatures are presented in Figures 2.7.1.5.6(a) through (d).

Table 2.7.1.0(b). Design Mechanical and Physical Properties of AISI 301and Other[a,b,c] Stainless Steel

Specification	AMS 5901	AMS 5517		AMS 5518		AMS 5902		AMS 5519	
Form	Sheet and strip								
Condition	Annealed	¼ Hard		½ Hard		¾ Hard		Full Hard	
Thickness, in.	≤0.187	...		...		...		...	
Basis	S	A	B	A	B	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	73	124	129	141	151	157	168	174	185
LT	75	122	127	142	152	163	173	175	186
F_{ty}, ksi:									
L	26	69	83	93	110	118	135	137	153
LT	30	67	82	92	105	113	133	125	142
F_{cy}, ksi:									
L	23	44	54	61	69	75	88	83	94
LT	29	71	88	100	116	127	152	142	164
F_{su}, ksi	50	66	69	77	82	88	93	95	100
F_{bru}, ksi:									
(e/D = 1.5)	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	162	262	273	292	310	327	342	346	361
F_{bry}, ksi:									
(e/D = 1.5)	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	55	123	149	167	189	202	234	222	249
e, percent (S basis):									
LT	40	25	...	[d]	...	[d]	...	[d]	...
E, 10^3 ksi:									
L	29.0	27.0		26.0		26.0		26.0	
LT	29.0	28.0		28.0		28.0		28.0	
E_c, 10^3 ksi:									
L	28.0	26.0		26.0		26.0		26.0	
LT	28.0	27.0		27.0		27.0		27.0	
G, 10^3 ksi	11.2	10.6		10.5		10.5		10.5	
μ	0.27	0.27		0.27		0.27		0.27	
Physical Properties:									
ω, lb/in.^{3}	0.286								
C, K, and α	See Figure 2.7.1.0								

a Properties also applicable to AISI 302 for the following; AMS5516 for annealed condition, AMS5903 for 1/4H condition, AMS5904 for 1/2H condition, AMS5905 for 3/4H condition, and AMS5906 for full hard condition.

b Properties also applicable to AISI 304 for the following; AMS 5513 for annealed condition, AMS 5910 for 1/4H condition, AMS 5911 for 1/2H condition, AMS 5912 for 3/4H condition, and AMS 5913 for full hard condition.

c Properties also applicable to AISI 316 for the following; AMS 5524 for annealed condition and AMS5907 for 1/4H condition.

d See Table 2.7.1.0(c).

Note: Yield strength, particularly in compression, and modulus of elasticity in the longitudinal direction may be raised appreciably by thermal stress-relieving treatment in the range 500 to 800°F.

Table 2.7.1.0(c). Minimum Elongation Values for AISI 301 Stainless Steel Sheet and Strip

Condition	Thickness, inches	Elongation (LT), percent
½ hard	0.015 and under	15
	0.016 and over	18
¾ hard	0.030 and under	10
	0.031 and over	12
Full hard	0.015 and under	8
	0.016 and over	9

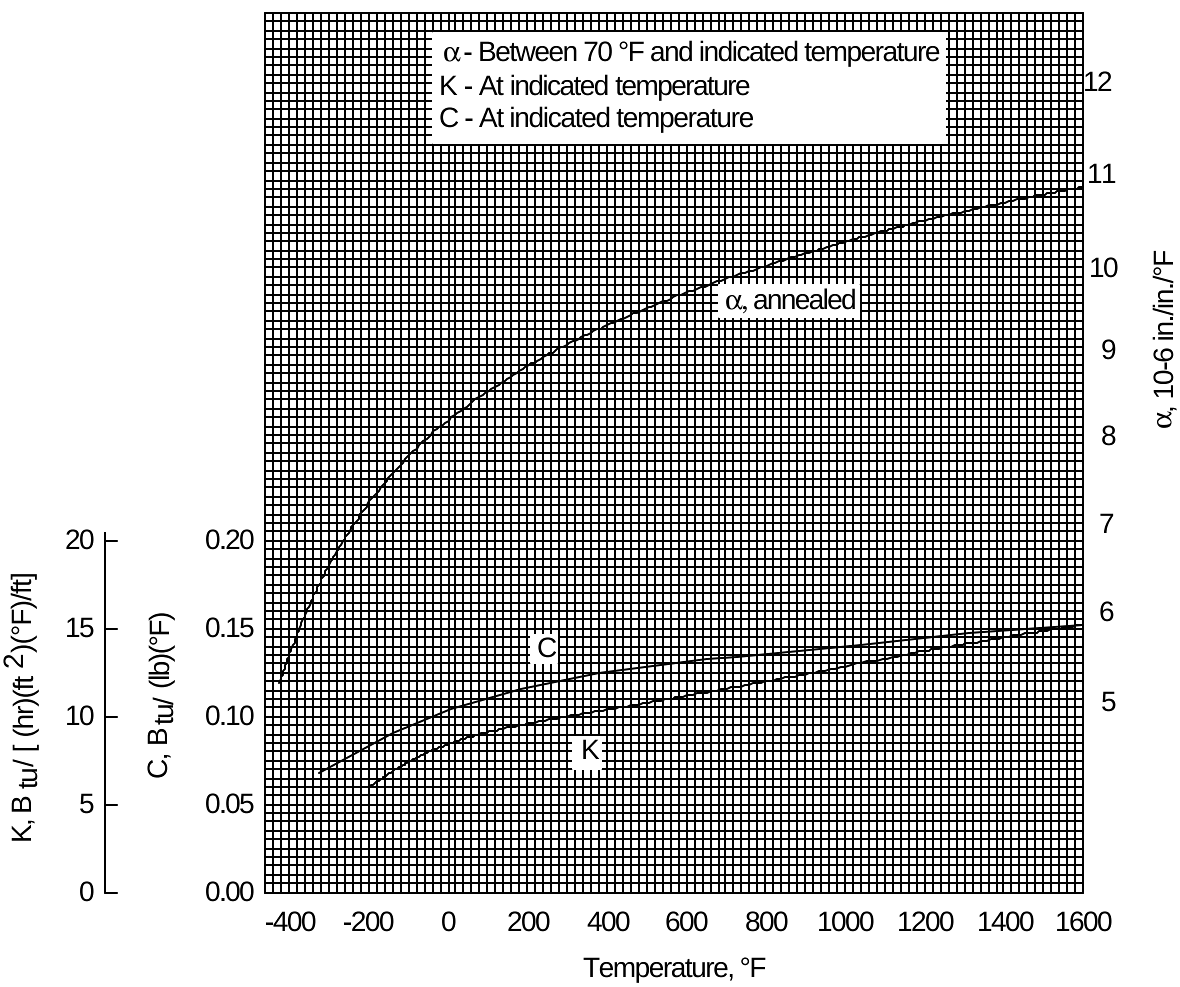

Figure 2.7.1.0. Effect of temperature on the physical properties of AISI 301 stainless steel.

Table 3.1.2.1.6. Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]

Alloy/Temper[b]	Product Form	Orien-tation[c]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi $\sqrt{in.}$ Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
2014-T651	Plate	L-T	≥0.5	1	24	0.5-1.0	25	22	19	8.4	
2014-T651	Plate	T-L	≥0.5	2	34	0.5-1.0	23	21	18	6.5	
2014-T652	Hand Forging	L-T	≥0.5	2	15	0.8-2.0	48	31	24	21.8	
2014-T652	Hand Forging	T-L	≥0.8	2	15	0.8-2.0	30	21	18	14.4	
2024-T351	Plate	L-T	≥1.0	2	11	0.8-2.0	43	31	27	16.5	
2024-T851	Plate	L-S	1.4-3.0	4	11	0.5-0.8	32	25	20	17.8	
2024-T851	Plate	L-T	≥0.5	11	102	0.4-1.4	32	23	15	10.1	
2024-T851	Plate	T-L	0.4-4.0	9	80	0.4-1.4	25	20	18	8.8	
2024-T852	Forging	T-L	2.0-7.0	3	20	0.7-2.0	25	19	15	15.5	
2024-T852	Hand Forging	L-T	----	4	35	0.8-2.0	38	28	19	18.4	
2024-T852	Hand Forging	T-L	----	2	17	0.7-2.0	22	18	14	14.4	
2124-T851	Plate	L-T	≥0.8	13	497	0.5-2.5	38	29	18	10.4	24
2124-T851	Plate	T-L	0.6-6.0	10	509	0.5-2.0	32	25	19	9.7	20
2124-T851	Plate	S-L	≥0.5	6	489	0.3-1.5	27	21	16	9.8	18
2219-T851	Plate	L-T	----	4	67	1.0-2.5	38	33	30	7.2	
2219-T851	Plate	T-L	≥1.0	6	108	0.8-2.5	37	29	20	10.1	
2219-T851	Plate	S-L	≥0.8	3	24	0.5-1.5	26	22	20	9.6	
2219-T851	Forging	S-L	----	1	85	1.0-1.5	34	25	19	12.1	
2219-T8511	Extrusion	T-L	----	1	19	1.8-2.0	34	29	23	12.3	
2219-T852	Forging	S-L	----	2	60	0.8-2.0	35	25	20	12.1	
2219-T852	Hand Forging	L-T	----	2	32	1.5-2.5	46	38	30	9.7	
2219-T852	Hand Forging	T-L	≥1.5	2	28	1.5-2.5	30	27	22	8.4	
2219-T87	Plate	L-T	≥1.5	3	11	0.8-2.0	34	27	25	9.3	
2219-T87	Plate	T-L	----	1	11	1.0	22	22	19	3.9	31
7040-T7451	Plate	L-T	3-4	1	16	2	39	37	34	5.2	26
7040-T7451	Plate	T-L	3-4	1	16	2	31	30	28	2.8	24
7040-T7451	Plate	S-L	3-4	1	14	2	33	31	29	4.2	30
7040-T7451	Plate	L-T	4-5	1	17	2	34	32	31	2.0	25
7040-T7451	Plate	T-L	4-5	1	17	2	27	26	26	1.5	24
7040-T7451	Plate	S-L	4-5	1	17	2	28	26	26	2.2	29
7040-T7451	Plate	L-T	5-6	1	17	2	34	32	30	2.7	23
7040-T7451	Plate	T-L	5-6	1	14	2	28	25	25	3.5	24
7040-T7451	Plate	S-L	5-6	1	16	2	28	27	26	2.7	27
7040-T7451	Plate	L-T	6-7	1	21	2	37	34	30	5.9	22
7040-T7451	Plate	T-L	6-7	1	21	2	29	27	25	2.8	23
7040-T7451	Plate	S-L	6-7	1	21	2	30	29	27	4.0	26
7040-T7451	Plate	L-T	7-8	1	18	2	33	32	30	3.2	22
7040-T7451	Plate	T-L	7-8	1	16	2	29	28	26	2.7	

a These values are for information only.
b Products that do not receive a mechanical stress-relieving process (e.g. -T73 & -T74 tempers) have the potential for induced residual stresses. As a result, care must be taken to prevent fracture toughness properties from bias resulting from residual stresses.
c Refer to Figure 1.4.12.3 for definition of symbols.
d Varies with thickness.

Table 3.1.2.1.6. Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]—Continued

Alloy/Temper[b]	Product Form	Orien-tation[c]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi$\sqrt{in.}$				
							Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
7040-T7451	Plate	S-L	7-8	1	13	2	31	29	26	4.6	23
7040-T7451	Plate	L-T	8-8.5	1	17	2	34	31	28	4.6	26
7040-T7451	Plate	T-L	8-8.5	1	13	2	26	24	23	5.0	22
7040-T7451	Plate	S-L	8-8.5	1	17	2	27	26	25	2.1	22
7049-T73	Die Forging	L-T	1.4	3	21	0.5-1.0	34	30	27	7.4	
7049-T73	Die Forging	S-L	≥0.5	3	46	0.5-1.0	26	22	18	9.7	
7049-T73	Hand Forging	L-T	≥0.5	2	28	0.5-1.0	37	30	23	12.1	
7049-T73	Hand Forging	T-L	2.0-7.1	2	27	1.0	28	22	18	12.5	
7049-T73	Hand Forging	S-L	1.0	2	24	0.8-1.0	22	19	14	14.2	
7050-T7351	Plate	L-T	1.0-6.0	2	31	1.0-2.0	43	35	28	11.3	
7050-T7351	Plate	T-L	2.0-6.0	1	29	1.5-2.0	35	30	25	8.5	
7050-T7351	Plate	S-L	2.0-6.0	1	30	0.8-1.5	30	28	25	4.6	
7050-T74	Die Forging	S-L	0.6-7.1	3	12	0.6-2.0	27	24	21	8.8	
7050-T7451	Plate	L-T	----	13	96	1.0-2.0	39	32	25	11.7	d
7050-T7451	Plate	T-L	≥1.0	9	97	0.5-2.0	38	28	21	15.6	d
7050-T7451	Plate	S-L	≥1.0	6	44	0.7-2.0	28	23	21	6.3	
7050-T7452	Hand Forging	L-T	3.5-5.5	1	11	1.5	34	31	26	8.0	d
7050-T7452	Hand Forging	T-L	3.5-7.5	1	13	1.5	22	21	18	6.7	d
7050-T7452	Hand Forging	S-L	3.5-7.5	1	17	0.8-1.5	21	19	16	7.5	
7050-T76511	Extrusion	L-T	----	2	38	0.6-2.0	40	31	27	7.8	d
7075-T651	Plate	L-T	≥0.6	7	99	0.5-2.0	30	26	20	7.6	d
7075-T651	Plate	T-L	≥0.5	5	135	0.4-2.0	27	22	18	8.9	
7075-T651	Plate	S-L	----	2	37	0.5-1.5	22	18	14	10.4	
7075-T6510	Extrusion	L-T	0.7-3.5	1	26	0.5-1.2	32	27	23	7.8	
7075-T6510	Extrusion	T-L	0.7-3.5	1	25	0.5-1.2	28	24	21	8.0	
7075-T6510	Forged Bar	L-T	0.7-5.0	1	13	0.6-2.0	35	29	24	11.6	
7075-T6510	Forged Bar	T-L	0.7-5.0	1	13	0.5-2.5	24	21	17	8.2	
7075-T73	Die Forging	T-L	≥0.5	1	22	0.5-0.8	25	21	18	9.9	
7075-T73	Hand Forging	L-T	----	2	10	1.0-1.5	39	31	29	8.8	
7075-T73	Hand Forging	T-L	≥1.0	2	14	1.0-1.5	27	23	20	9.0	
7075-T7351	Plate	L-T	≥1.0	8	65	0.5-2.0	36	30	25	8.2	
7075-T7351	Plate	T-L	≥0.5	6	56	0.5-2.0	47	27	21	20.1	
7075-T7351	Plate	S-L	≥0.5	3	20	0.5-1.5	38	22	17	32.5	
7075-T73511	Extrusion	T-L	1.0-7.0	1	19	0.9-1.0	22	20	19	3.7	
7075-T73511	Extrusion	L-T	≥0.9	3	28	0.7-2.0	43	35	31	9.4	

a These values are for information only.
b Products that do not receive a mechanical stress-relieving process (e.g. -T73 & -T74 tempers) have the potential for induced residual stresses. As a result, care must be taken to prevent fracture toughness properties from bias resulting from residual stresses.
c Refer to Figure 1.4.12.3 for definition of symbols.

Table 3.1.2.1.6. Values of Room-Temperature Plane-Strain Fracture Toughness of Aluminum Alloys[a]—Continued

Alloy/Temper[b]	Product Form	Orien-tation[c]	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	K_{IC}, ksi$\sqrt{in.}$				
							Max.	Avg.	Min.	Coefficient of Variation	Minimum Specification Value
7075-T73511	Extrusion	T-L	≥0.7	3	35	0.5-1.8	35	23	12	20.3	
7075-T73511	Extrusion	S-L	≥0.5	3	15	0.4-1.0	22	20	17	9.0	
7075-T7352	Hand Forging	L-T	----	2	27	0.8-2.0	39	33	30	9.2	
7075-T7352	Hand Forging	T-L	≥0.8	3	20	0.8-2.0	33	26	23	9.9	
7075-T7651	Plate	L-T	≥0.8	6	82	0.5-2.0	43	29	22	17.8	
7075-T7651	Plate	T-L	≥0.5	7	96	0.5-2.0	28	23	20	7.6	
7075-T7651	Plate	S-L	≥0.5	5	28	0.4-0.8	20	18	15	7.7	
7075-T7651	Clad Plate	L-T	0.5-0.6	2	30	0.5-0.6	30	25	22	7.1	
7075-T7651	Clad Plate	T-L	0.5-0.6	2	56	0.5-0.6	28	24	21	7.7	
7075-T76511	Extrusion	L-T	1.3-7.0	4	11	1.2-2.0	41	35	31	11.0	
7075-T76511	Extrusion	T-L	1.2	3	42	0.6-2.0	36	23	20	15.5	
7175-T6/T6511	Extrusion	T-L	----	2	25	0.8-1.0	24	21	18	7.9	
7175-T651	Plate	L-T	----	1	17	0.7-0.8	30	26	24	9.2	
7175-T651	Plate	T-L	----	1	10	0.7-0.8	26	22	20	9.8	
7175-T6511	Extrusion	L-T	----	2	14	0.8-1.0	36	32	24	13.8	
7175-T7351	Plate	L-T	----	2	30	0.7-1.6	36	33	32	3.3	
7175-T7351	Plate	T-L	----	2	32	0.7-1.6	30	27	25	4.5	
7175-T73511	Extrusion	L-T	≥0.7	5	43	0.5-1.5	47	33	23	16.0	30
7175-T73511	Extrusion	T-L	≥0.5	5	43	0.5-1.5	35	25	20	10.9	22
7175-T74	Die Forging	L-T	≥0.5	3	14	0.5-1.0	38	30	22	15.0	27
7175-T74	Die Forging	T-L	≥0.5	2	13	0.5-1.0	33	24	21	15.7	21
7175-T74	Die Forging	S-L	≥0.5	4	41	0.5-0.8	31	26	20	8.6	21
7175-T74	Hand Forging	T-L	3.0-5.0	2	10	1.0-1.5	29	26	24	4.8	25
7175-T7651	Clad Plate	L-T	----	1	53	1.5	33	32	30	4.3	
7175-T7651	Clad Plate	T-L	----	1	50	0.6	28	27	25	3.1	
7175-T7651	Plate	L-T	----	1	12	1.5	32	32	31	1.7	
7175-T7651	Plate	T-L	----	1	11	1.5	26	25	24	3.3	
7175-T76511	Extrusion	L-T	1.4-3.8	2	48	0.6-2.0	39	33	27	10.7	
7175-T76511	Extrusion	T-L	≥0.6	4	49	0.6-1.8	31	22	20	9.8	
7475-T651	Plate	L-T	----	3	34	0.9-2.0	49	38	33	9.2	30
7475-T651	Plate	T-L	0.6-2.0	2	143	0.6-2.0	43	34	27	9.8	28
7475-T651	Plate	S-L	≥0.6	1	23	0.5-1.0	36	28	20	14.9	
7475-T7351	Plate	L-T	1.3-4.0	8	151	1.3-3.0	60	47	34	10.4	d
7475-T7351	Plate	T-L	≥1.3	7	132	0.7-3.0	50	37	29	10.4	d
7475-T7351	Plate	S-L	≥0.7	7	74	0.5-1.5	36	30	25	8.7	25
7475-T7651	Plate	L-T	1.0-2.0	4	10	1.0-2.0	46	41	36	6.2	33
7475-T7651	Plate	T-L	≥1.0	2	15	0.9-2.0	50	36	29	14.5	30

a These values are for information only.
b Products that do not receive a mechanical stress-relieving process (e.g. -T73 & -T74 tempers) have the potential for induced residual stresses. As a result, care must be taken to prevent fracture toughness properties from bias resulting from residual stresses.

The tensile and shear moduli of aluminum alloys also increase with decreasing temperature so that at -100, -320, and -423°F, they are approximately 5, 12, and 16 percent, respectively, above the room temperature values [Reference 3.1.2.1.7(f)].

3.1.2.1.8 *Elevated Temperatures* — In general, the strengths of aluminum alloys decrease and toughness increases with increase in temperature and with time at temperature above room temperature; the effect is generally greatest over the temperature range from 212 to 400°F. Exceptions to the general trends are tempers developed by solution heat treatment without subsequent aging, for which the initial elevated temperature exposure results in some age hardening and reduction in toughness; further time at temperature beyond that required to achieve peak hardness results in the aforementioned decrease in strength and increase in toughness [Reference 3.1.2.1.8].

3.1.2.2 *Physical Properties* — Where available from the literature, the average values of certain physical properties are included in the room-temperature tables for each alloy. These properties include density, ω, in lb/in.^{3}; the specific heat, C, in Btu/(lb)(°F); the thermal conductivity, K, in Btu/[(hr)(ft^2)(°F)/ft]; and the mean coefficient of thermal expansion, α, in in./in./°F. Where more extensive data are available to show the effect of temperature on these physical properties, graphs of physical property as a function of temperature are presented for the applicable alloys.

3.1.2.3 *Corrosion Resistance* —

3.1.2.3.1 *Resistance to Stress-Corrosion Cracking [see References 3.1.2.3.1(a) through (d)]* — In-service stress-corrosion cracking failures can be caused by stresses produced from a wide variety of sources, including solution heat treatment, straightening, forming, fit-up, clamping, and sustained service loads. These stresses may be tensile or compressive, and the stresses due to Poisson effects should not be ignored because SCC failures can be caused by sustained shear stresses. Pin-hole flaws in some corrosion protection coatings may also be sufficient to allow SCC to occur. The high-strength heat treatable wrought aluminum alloys in certain tempers are susceptible to stress-corrosion cracking, depending upon product, section size, direction and magnitude of stress. These alloys include 2014, 2025, 2618, 7075, 7150, 7175, and 7475 in the T6-type tempers and 2014, 2024, 2124, and 2219 in the T3 and T4-type tempers. Other alloy-temper combinations, notably 2024, 2124, 2219, and 2519 in the T6- or T8-type tempers and 7010, 7049, 7050, 7075, 7149, 7175, and 7475 in the T73-type tempers, are decidedly more resistant and sustained tensile stresses of 50 to 75 percent of the minimum yield strength may be permitted without concern about stress corrosion cracking. The T74 and T76 tempers of 7010, 7075, 7475, 7049, 7149, and 7050 provide an intermediate degree of resistance to stress-corrosion cracking, i.e., superior to that of the T6 temper, but not as good as that of the T73 temper of 7075. To assist in the selection of materials, letter ratings indicating the relative resistance to stress-corrosion cracking of various mill product forms of the wrought 2000, 6000, and 7000 series heat-treated aluminum alloys are presented in Table 3.1.2.3.1(a). This table is based upon ASTM G 64 which contains more detailed information regarding this rating system and the procedure for determining the ratings. In addition, more quantitative information in the form of the maximum specified tension stresses at which test specimens will not fail when subjected to the alternate immersion stress-corrosion test described in ASTM G 47 are shown in Tables 3.1.2.3.1(b) through (e) for various heat-treated aluminum product forms, alloys, and tempers.

Where short times at elevated temperatures of 150 to 500°F may be encountered, the precipitation heat-treated tempers of 2024 and 2219 alloys are recommended over the naturally aged tempers.

Alloys 5083, 5086, and 5456 should not be used under high constant applied stress for continuous service at temperatures exceeding 150°F, because of the hazard of developing susceptibility to stress-corrosion cracking. In general, the H34 through H38 tempers of 5086, and the H32 through H38 tempers

Table 3.1.2.3.1(a). Resistance to Stress-Corrosion Ratings[a] for High-Strength Aluminum Alloy Products

Alloy and Temper[b]	Test Direction[c]	Rolled Plate	Rod and Bar[d]	Extruded Shapes	Forging
2014-T6	L	A	A	A	B
	LT	B[e]	D	B[e]	B[e]
	ST	D	D	D	D
2024-T3, T4	L	A	A	A	[f]
	LT	B[e]	D	B[e]	[f]
	ST	D	D	D	[f]
2024-T6	L	[f]	A	[f]	A
	LT	[f]	B	[f]	A[e]
	ST	[f]	B	[f]	D
2024-T8	L	A	A	A	A
	LT	A	A	A	A
	ST	B	A	B	C
2124-T8	L	A	[f]	[f]	[f]
	LT	A	[f]	[f]	[f]
	ST	B	[f]	[f]	[f]
2219-T351X, T37	L	A	[f]	A	[f]
	LT	B	[f]	B	[f]
	ST	D	[f]	D	[f]
2219-T6	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A
2219-T85XX, T87	L	A	[f]	A	A
	LT	A	[f]	A	A
	ST	A	[f]	A	A
6061-T6	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A
7040-T7451	L	A	[f]	[f]	[f]
	LT	A	[f]	[f]	[f]
	ST	B	[f]	[f]	[f]
7049-T73	L	A	[f]	A	A
	LT	A	[f]	A	A
	ST	A	[f]	B	A
7049-T76	L	[f]	[f]	A	[f]
	LT	[f]	[f]	A	[f]
	ST	[f]	[f]	C	[f]
7050-T74	L	A	[f]	A	A
	LT	A	[f]	A	A
	ST	B	[f]	B	B
7050-T76	L	A	A	A	[f]
	LT	A	B	A	[f]
	ST	C	B	C	[f]
7075-T6	L	A	A	A	A
	LT	B[e]	D	B[e]	B[e]
	ST	D	D	D	D
7075-T73	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A

Table 3.1.2.3.1(a). Resistance to Stress-Corrosion Ratings[a] for High-Strength Aluminum Alloy Products—Continued

Alloy and Temper[b]	Test Direction[c]	Rolled Plate	Rod and Bar[d]	Extruded Shapes	Forging
7075-T74	L	[f]	[f]	[f]	A
	LT	[f]	[f]	[f]	A
	ST	[f]	[f]	[f]	B
7075-T76	L	A	[f]	A	[f]
	LT	A	[f]	A	[f]
	ST	C	[f]	C	[f]
7149-T73	L	[f]	[f]	A	A
	LT	[f]	[f]	A	A
	ST	[f]	[f]	B	A
7175-T74	L	[f]	[f]	[f]	A
	LT	[f]	[f]	[f]	A
	ST	[f]	[f]	[f]	B
7475-T6	L	A	[f]	[f]	[f]
	LT	B[e]	[f]	[f]	[f]
	ST	D	[f]	[f]	[f]
7475-T73	L	A	[f]	[f]	[f]
	LT	A	[f]	[f]	[f]
	ST	A	[f]	[f]	[f]
7475-T76	L	A	[f]	[f]	[f]
	LT	A	[f]	[f]	[f]
	ST	C	[f]	[f]	[f]

a Ratings were determined from stress corrosion tests performed on at least ten random lots for which test results showed 90% conformance with 95% confidence when tested at the following stresses.

A - Equal to or greater than 75% of the specified minimum yield strength. A very high rating. SCC not anticipated in general applications if the total sustained tensile stress* is less than 75% of the minimum specified yield stress for the alloy, heat treatment, product form, and orientation.

B - Equal to or greater than 50% of the specified minimum yield strength. A high rating. SCC not anticipated if the total sustained tensile stress* is less than 50% of the specified minimum yield stress.

C - Equal to or greater than 25% of the specified minimum yield stress or 14.5 ksi, whichever is higher. An intermediate rating. SCC not anticipated if the total sustained tensile stress* is less than 25% of the specified minimum yield stress. This rating is designated for the short transverse direction in improved products used primarily for high resistance to exfoliation corrosion in relatively thin structures where applicable short transverse stresses are unlikely.

D - Fails to meet the criterion for the rating C. A low rating. SCC failures have occurred in service or would be anticipated if there is any sustained tensile stress* in the designated test direction. This rating currently is designated only for the short transverse direction in certain materials.

NOTE - The above stress levels are not to be interpreted as “threshold” stresses, and are not recommended for design. Other documents, such as MIL-STD-1568, NAS SD-24, and MSFC-SPEC-522A, should be consulted for design recommendations.

* The sum of all stresses, including those from service loads (applied), heat treatment, straightening, forming, etc.

Table 3.1.2.3.1(a). Resistance to Stress-Corrosion Ratings[a] for High Strength Aluminum Alloy Products—Continued

b The ratings apply to standard mill products in the types of tempers indicated, including stress-relieved tempers, and could be invalidated in some cases by application of nonstandard thermal treatments of mechanical deformation at room temperature by the user.

c Test direction refers to orientation of the stressing direction relative to the directional grain structure typical of wrought materials, which in the case of extrusions and forgings may not be predictable from the geometrical cross section of the product.
L—Longitudinal: parallel to the direction of principal metal extension during manufacture of the product.
LT—Long Transverse: perpendicular to direction of principal metal extension. In products whose grain structure clearly shows directionality (width to thickness ratio greater than two) it is that perpendicular direction parallel to the major grain dimension.
ST—Short Transverse: perpendicular to direction of principal metal extension and parallel to minor dimension of grains in products with significant grain directionality.

d Sections with width-to-thickness ratio equal to or less than two for which there is no distinction between LT and ST.

e Rating is one class lower for thicker sections: extrusion, 1 inch and over; plate and forgings, 1.5 inches and over.

f Ratings not established because the product is not offered commercially.

NOTE: This table is based upon ASTM G 64.

Table 3.1.2.3.1(b). Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[a] for Various Stress Corrosion Resistant Aluminum Alloy Plate

Alloy and Temper	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
2024-T851	ST	1.001-4.000	28[b]	Company specification
		4.001-6.000	27[b]	
2090-T81[c]	ST	0.750-1.500	20	AMS 4303
2124-T851	ST	1.500-1.999	28[b]	AMS 4101
		2.000-4.000	28[b]	AMS-QQ-A-0025/29, ASTM B 209, AMS 4101
		4.001-6.000	27[b]	
2124-T8151[c]	ST	1.500-3.000	30[b]	AMS 4221
		3.001-5.000	29[b]	
		5.001-6.000	28[b]	
2219-T851	ST	0.750-2.000	34[d]	AMS-QQ-A-250/30
		2.001-4.000	33[d]	
		4.001-5.000	32[d]	
		5.001-6.000	31[d]	
2219-T87	ST	0.750-3.000	38[d]	AMS-QQ-A-250/30
		3.001-4.000	37[d]	
		4.001-5.000	36[d]	
2519-T87	ST	0.750-4.000	43[d]	MIL-A-46192
7010-T7351[c]	ST	0.750-3.000	41[d]	AMS 4203
		3.001-5.000	40[d]	
		5.001-5.500	39[d]	
7010-T7451	ST	0.750-3.000	31[b]	AMS 4205
		3.001-5.500	35	
7010-T7651	ST	0.750-5.500	25	AMS 4204
7049-T7351	ST	0.750-5.000	45	AMS 4200
7050-T7451	ST	0.750-6.000	35	AMS 4050
7050-T7651	ST	0.750-3.000	25	AMS 4201
7075-T7351	ST	0.750-2.000	42[d]	AMS-QQ-A-250/12, AMS 4078, ASTM B 209
		2.001-2.500	39[d]	
		2.501-4.000	36[d]	
7075-T7651	ST	0.750-1.000	25	AMS-QQ-A-00250/24, ASTM B 209
Clad 7075-T7651	ST	0.750-1.000	25	AMS-QQ-A-00250/25, ASTM B 209
7150-T7751	ST	0.750-3.000	25	AMS 4252
7475-T7351	ST	0.750-4.000	40	AMS 4202
7475-T7651	ST	0.750-1.500	25	AMS 4089

a Most specifications reference ASTM G 47, which requires exposures of 10 days for 2XXX alloys and 20 days for 7XXX alloys in ST test direction.

b 50% of specified minimum long transverse yield strength.

c Design values are not included in MIL-HDBK-5.

d 75% of specified minimum long transverse yield strength.

DO NOT USE STRESS VALUES FOR DESIGN

Table 3.1.2.3.1(c). Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[a] for Various Stress Corrosion Resistant Aluminum Alloy Rolled Bars, Rods, and Extrusions

Alloy and Temper	Product Form	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
7075-T73-T7351	Rolled Bar and Rod	ST	0.750-3.000	42[b]	AMS-QQ-A-225/9, AMS 4124, ASTM B211
2219-T8511	Extrusion	ST	0.750-3.000	30	AMS 4162, AMS 4163
7049-T73511	Extrusion	ST	0.750-2.999	41[c]	AMS 4157
			3.000-5.000	40[c]	
7049-T76511[d]	Extrusion	ST	0.750-5.000	20	AMS 4159
7050-T73511	Extrusion	ST	0.750-5.000	45	AMS 4341
7050-T74511	Extrusion	ST	0.750-5.000	35	AMS 4342
7050-T76511	Extrusion	ST	0.750-5.000	17	AMS 4340
7075-T73-T73510-T73511	Extrusion	ST	0.750-1.499	45[b]	AMS-QQ-A-200/11, AMS 4166, AMS 4167, ASTM B
			1.500-2.999	44[b]	211
			3.000-4.999	42[b]	
			3.000-4.999	41[b,e]	
7075-T76-T76510-T76511	Extrusion	ST	0.750-1.000	25	
7149-T73511[d]	Extrusion	ST	0.750-2.999	41[c]	AMS-QQ-A-200/15, ASTM B 221
			3.000-5.000	40[c]	AMS 4543
7150-T77511	Extrusion	ST	0.750-2.000	25	
7175-T73511	Extrusion	ST	0.750-2.000	44	AMS 4345
					AMS 4344

a Most specifications reference ASTM G 47, which requires exposures of 10 days for 2XXX alloys and 20 days for 7XXX alloys in ST test direction.
b 75% of specified minimum longitudinal yield strength.
c 65% of specified minimum longitudinal yield strength.
d Design values are not included in MIL-HDBK-5.
e Over 20 square inches cross-sectional area.

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Table 3.1.2.3.1(d). Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[a] for Various Stress Corrosion Resistant Aluminum Die Forgings

Alloy and Temper	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
7049-T73	ST	0.750-2.000	46[b]	QQ-A-367, AMS 4111, ASTM B 247
		2.001-5.000	45[b]	
7050-T74	ST	0.750-6.000	35	AMS 4107
7050-T7452	ST	0.750-4.000	35	AMS 4333
7075-T73	ST	0.750-3.000	42[b]	MIL-A-22771, QQ-A-367
		3.001-4.000	41[b]	AMS 4241, ASTM B 247
		4.001-5.000	39[b]	AMS 4141
		5.001-6.000	38[b]	
7075-T7352	ST	0.750-4.000	42[b]	MIL-A-22771, QQ-A-367, AMS 4147, ASTM B 247
		3.001-4.000	39[b]	
7075-T7354[c]	ST	0.750-3.000	42	Company Specification
7075-T74[c]	ST	0.750-3.000	35	AMS 4131
		3.001-4.000	31[d]	
		4.001-5.000	30[d]	
		5.001-6.000	29[d]	
7149-T73	ST	0.750-2.000	46[b]	AMS 4320
		2.001-5.000	45[b]	
7175-T74	ST	0.750-3.000	35	AMS 4149, ASTM B 247
		3.001-4.000	31[d]	AMS 4149
		4.001-5.000	30[d]	
		5.001-6.000	29[d]	
7175-T7452[c]	ST	0.750-3.000	35	AMS 4179

a Most specifications Reference ASTM G 47, which requires 20 days of exposure for 7XXX alloys in ST test direction.
b 75% of specified minimum longitudinal yield strength.
c Design values are not included in MIL-HDBK-5.
d 50% of specified minimum longitudinal yield strength.

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Table 3.1.2.3.1(e). Maximum Specified Tension Stress at Which Test Specimens Will Not Fail in 3½% NaCl Alternate Immersion Test[a] for Various Stress Corrosion Resistant Aluminum Hand Forgings

Alloy and Temper	Test Direction	Thickness, inches	Stress, ksi	Referenced Specifications
7049-T73	ST	2.001-3.000	45[b]	QQ-A-367, AMS 4111, ASTM B 247
		3.001-4.000	44[b]	
		4.001-5.000	42[b]	
7049-T7352[c]	ST	0.750-3.000	44[b]	AMS 4247
		3.001-4.000	43[b]	
		4.001-5.000	40[b]	
7050-T7452	ST	0.750-8.000	35	AMS 4108
7075-T73	ST	0.750-3.000	42[b]	MIL-A-22771, QQ-A-367, ASTM B 247
		3.001-4.000	41[b]	
		4.001-4.000	39[b]	
		5.001-6.000	38[b]	
7075-T7352	ST	0.750-3.000	39[d]	AMS 4147
		3.001-4.000	37[d]	
		4.001-5.000	36[d]	
		5.001-6.000	34[d]	
7075-T74[c]	ST	0.750-3.000	35	AMS 4131
		3.001-4.000	30[e]	
		4.001-5.000	28[e]	
		5.001-6.000	27[e]	
7075-T7452[c]	ST	0.750-2.000	35	AMS 4323
		2.001-3.000	29[f]	
		3.001-4.000	28[f]	
		4.001-5.000	26[f]	
		5.001-6.000	24[f]	
7149-T73	ST	2.000-3.000	44[d]	AMS 4320
		3.001-4.000	43[d]	
		4.001-5.000	42[d]	
7175-T74	ST	0.750-3.000	35	AMS 4149
		3.001-4.000	29[f]	
		4.001-5.000	28[f]	
		4.001-6.000	26[f]	
7175-T7452	ST	0.750-3.000	35	AMS 4179
		3.001-4.000	27[f]	
		4.001-5.000	26[f]	
		5.001-6.000	24[f]	

a Most specifications Reference ASTM G 47, which requires 20 days of exposure for 7XXX alloys in ST test direction.
b 75% of specified minimum longitudinal yield strength.
c Design values are not included in MIL-HDBK-5.
d 75% of specified minimum long transverse yield strength.
e 50% of specified minimum longitudinal yield strength.
f 50% of specified minimum long transverse yield strength.

DO NOT USE STRESS VALUES FOR DESIGN

of 5083 and 5456 are not recommended, because these tempers can become susceptible to stress-corrosion cracking.

For the cold forming of 5083 sheet and plate in the H112, H321, H323, and H343 tempers and 5456 sheet and plate in the H112 and H321 tempers, a minimum bend radius of 5T should be used. Hot forming of the O temper for alloys 5083 and 5456 is recommended, and is preferred to the cold worked tempers to avoid excessive cold work and high residual stress. If the cold worked tempers are heat-treatable alloys are heated for hot forming, a slight decrease in mechanical properties, particularly yield strength, may result.

3.1.2.3.2 *Resistance to Exfoliation [Reference 3.1.2.3.2]* — The high-strength wrought aluminum alloys in certain tempers are susceptible to exfoliation corrosion, dependent upon product and section size. Generally those alloys and tempers that have the lowest resistance to stress-corrosion cracking also have the lowest resistance to exfoliation. The tempers that provide improved resistance to stress-corrosion cracking also provide improved resistance or immunity to exfoliation. For example, the T76 temper of 7075, 7049, 7050, and 7475 provides a very high resistance to exfoliation, i.e., decidedly superior to the T6 temper, and almost the immunity provided by the T73 temper of 7075 alloy (see Reference 3.1.2.3.2).

3.1.3 MANUFACTURING CONSIDERATIONS

3.1.3.1 ***Avoiding Stress-Corrosion Cracking*** — In order to avoid stress-corrosion cracking (see Section 3.1.2.3), practices, such as the use of press or shrink fits; taper pins; clevis joints in which tightening of the bolt imposes a bending load on female lugs; and straightening or assembly operations; which result in sustained surface tensile stresses (especially when acting in the short-transverse grain orientation), should be avoided in these high-strength alloys: 2014-T451, T4, T6, T651, T652; 2024-T3, T351, T4; 7075-T6, T651, T652; 7150-T6151, T61511; and 7475-T6, T651.

Where straightening or forming is necessary, it should be performed when the material is in the freshly quenched condition or at an elevated temperature to minimize the residual stress induced. Where elevated temperature forming is performed on 2014-T4 T451, or 2024-T3 T351, a subsequent precipitation heat treatment to produce the T6 or T651, T81 or T851 temper is recommended.

It is good engineering practice to control sustained short-transverse tensile stress at the surface of structural parts at the lowest practicable level. Thus, careful attention should be given in all stages of manufacturing, starting with design of the part configuration, to choose practices in the heat treatment, fabrication, and assembly to avoid unfavorable combinations of end grain microstructure and sustained tensile stress. The greatest danger arises when residual, assembly, and service stress combine to produce high sustained tensile stress at the metal surface. Sources of residual and assembly stress have been the most contributory to stress-corrosion-cracking problems because their presence and magnitude were not recognized. In most cases, the design stresses (developed by functional loads) are not continuous and would not be involved in the summation of sustained tensile stress. It is imperative that, for materials with low resistance to stress-corrosion cracking in the short-transverse grain orientation, every effort be taken to keep the level of sustained tensile stress close to zero.

3.1.3.2 ***Cold-Formed Heat-Treatable Aluminum Alloys*** — Cold working such as stretch forming of aluminum alloy prior to solution heat treatment may result in recrystallization or grain growth during heat treatment. The resulting strength, particularly yield strength, may be significantly below the specified minimum values. For critical applications, the strength should be determined on the part after forming and heat treating including straightening operations. To minimize recrystallization during heat treatment, it is recommended that forming be done after solution heat treatment in the as-quenched condition whenever possible, but this may result in compressive yield strength in the direction of stretching being lower than MIL-HDBK-5 design allowables for user heat treat tempers.

3.1.3.3 *Dimensional Changes* — The dimensional changes that occur in aluminum alloy during thermal treatment generally are negligible, but in a few instances these changes may have to be considered in manufacturing. Because of many variables involved, there are no tabulated values for these dimensional changes. In the artificial aging of alloy 2219 from the T42, T351, and T37 tempers to the T62, T851, and T87 tempers, respectively, a net dimensional growth of 0.00010 to 0.0015 in./in. may be anticipated. Additional growth of as much as 0.0010 in./in. may occur during subsequent service of a year or more at 300EF or equivalent shorter exposures at higher temperatures. The dimensional changes that occur during the artificial aging of other wrought heat-treatable alloys are less than one-half that for alloy 2219 under the same conditions.

3.1.3.4 *Welding* — The ease with which aluminum alloys may be welded is dependent principally upon composition, but the ease is also influenced by the temper of the alloy, the welding process, and the filler metal used. Also, the weldability of wrought and cast alloys is generally considered separately.

Several weldability rating systems are established and may be found in publications by the Aluminum Association, American Welding Society, and the American Society for Metals. Handbooks from these groups can be consulted for more detailed information. Specification AA-R-566 also contains useful information. This document follows most of these references in adopting a four level rating system. An "A" level, or readily weldable, means that the alloy (and temper) is routinely welded by the indicated process using commercial procedures. A "B" level means that welding is accomplished for many applications, but special techniques are required, and the application may require preliminary trials to develop procedures and tests to demonstrate weld performance. A "C" level refers to limited weldability because crack sensitivity, loss of corrosion resistance, and/or loss of mechanical properties may occur. A "D" level indicates that the alloy is not commercially weldable.

The weldability of aluminum alloys is rated by alloy, temper, and welding process (arc or resistance). Tables 3.1.3.4(a) and (b) list the ratings in the alloy section number order in which they appear in Chapter 3.

When heat-treated or work-hardened materials of most systems are welded, a loss of mechanical properties generally occurs. The extent of the loss (if not reheat treated) over the table strength allowables will have to be established for each specific situation.

Table 3.1.3.4(a). Fabrication Weldability of Wrought Aluminum Alloys

MIL-HDBK-5 Section No.	Alloy	Tempers	Weldability[a,b]	
			Inert Gas Metal or Tungsten Arc	Resistance Spot[c]
3.2.1	2014	O	C	D
		T6, T62, T651, T652, T6510, T6511	B	B
3.2.2	2017	T4, T42, T451	C	B
3.2.3	2024	O	D	D
		T3, T351, T361, T4, T42	C	B
		T6, T62, T81, T851, T861	C	B
		T8510, T8511, T3510, T3511	C	B
3.2.4	2025	T6	C	B
3.2.5	2090	T83	B	B
3.2.6	2124	T851	C	B
3.2.7	2219	O	A	B-D
		T62, T81, T851, T87, T8510, T8511	A	A
3.2.8	2618	T61	C	B
3.2.9	2519	T87	A	...
3.5.1	5052	O	A	B
		H32, H34, H36, H38	A	A
3.5.2	5083	O	A	B
		H321, H323, H343, H111, H112	A	A
3.5.3	5086	O	A	B
		H32, H34, H36, H38, H111, H112	A	A
3.5.4	5454	O	A	B
		H32, H34, H111, H112	A	A
3.5.5	5456	O	A	B
		H111, H321, H112	A	A
3.6.1	6013	T6	A	A
3.6.2	6061	O	A	B
		T4, T42, T451, T4510, T4511, T6	A	A
		T62, T651, T652, T6510, T6511	A	A
3.6.3	6151	T6	A	A
3.7.1	7010	All	C	B
3.7.2	7040	All	C	B
3.7.3	7049	All	C	B
	7149			
3.7.4	7050	All	C	B
3.7.5	7055			
3.7.6	7075	All	C	B
3.7.7	7150	All	C	B
3.7.8	7175	All	C	B
3.7.9	7249			
3.7.10	7475	All	C	B

a Ratings A through D are relative ratings defined as follows:
A - Generally weldable by all commercial procedures and methods.
B - Weldable with special techniques or for specific applications which justify preliminary trials or testing to develop welding procedures and weld performance.
C - Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties.
D - No commonly used welding methods have been developed.

b When using filler wire, the wire should contain less than 0.0008 percent beryllium to avoid toxic fumes.

c See MIL-W-6858 for permissible combinations.

Table 3.1.3.4(b). Fabrication Weldability[a] of Cast Aluminum Alloys

MIL-HDBK-5 Section No.	Alloy	Weldability[b,c]	
		Inert Gas Metal or Tungsten Arc	Resistance Spot
3.8.1	A201.0	C	C
3.9.1	354.0	B	B
3.9.2	355.0	B	B
3.9.3	C355.0	B	B
3.9.4	356.0	A	A
3.9.5	A356.0	A	A
3.9.6	A357.0	A	B
3.9.7	D357.0	A	A
3.9.8	359.0	A	B

a Weldability related to joining a casting to another part of same composition. The weldability ratings are not applicable to minor weld repairs. Such repairs shall be governed by the contractors procedure for in-process welding of castings, after approval by the procuring agency.

b Ratings A through D are relative ratings defined as follows:
- A - Generally weldable by all commercial procedures and methods.
- B - Weldable with special techniques or for specific applications which justify preliminary trials or testing to develop welding procedure and weld performance.
- C - Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties.
- D - No commonly used welding methods have been developed.

c When using filler wire, the wire should contain less than 0.0008 percent beryllium to avoid toxic fumes.

3.2 2000 SERIES WROUGHT ALLOYS

Alloys of the 2000 series contain copper as the principal alloying element and are strengthened by solution heat treatment and aging. As a group, these alloys are noteworthy for their excellent strengths at elevated and cryogenic temperatures, and creep resistance at elevated temperatures.

3.2.1 2014 ALLOY

3.2.1.0 ***Comments and Properties*** — 2014 is an Al-Cu alloy available in a wide variety of product forms. As shown in Table 3.1.2.3.1(a), 2014-T6 rolled plate, rod and bar, extruded shapes, and forgings have a 'D' SCC rating. This is the lowest rating and means that SCC failures have occurred in service or would be anticipated if there is any sustained stress. In-service failures are caused by stressed produced by any combination of sources including solution heat treatment, straightening, forming, fit-up, clamping, sustained service loads, or high service compression stresses that produce residual tensile stresses. These stresses may be tension or compression as well as the stresses due to the Poisson effect, because the actual failures are caused by the resulting sustained shear stresses. Pin-hole flaws in corrosion protection are sufficient for SCC. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 2014 aluminum alloy are presented in Table 3.2.1.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.2.1.0(b) through (g). Stress-strain parameters in accordance with Section 9.3.2.5 are given in Table 3.2.1.0(h). Figure 3.2.1.0 shows the effect of temperature on the physical properties of 2014 alloy.

Table 3.2.1.0(a). Material Specifications for 2014 Aluminum Alloy

Specification	Form
AMS 4028	Bare sheet and plate
AMS 4029	Bare sheet and plate
AMS-QQ-A-250/3	Clad sheet and plate
AMS-QQ-A-225/4	Rolled or drawn bar, rod, and shapes
AMS 4121	Bar and rod, rolled or cold finished
AMS-QQ-A-200/2	Extruded bar, rod, and shapes
AMS 4153	Extrusion
MIL-A-22771	Forging
QQ-A-367	Forging
AMS 4133	Forging

The temper index for 2014 is as follows:

Section	Temper
3.2.1.1	T6, T62, T651, T652, T6510, and T6511

3.2.1.1 ***T6, T62, T651, T652, T6510, and T6511 Temper***— Figures 3.2.1.1.1(a) through 3.2.1.1.5(b) present elevated-temperature curves for various mechanical properties. Figures 3.2.1.1.6(a) through (r) present tensile and compressive stress-strain and tangent-modulus curves for various tempers, product forms, and temperatures. Figures 3.2.1.1.6(s) through (v) are full-range tensile stress-strain curves for various products and tempers. Figures 3.2.1.1.8(a) through (e) contain S/N fatigue curves for various wrought products in the T6 temper.

Table 3.2.1.0(d). Design Mechanical and Physical Properties of 2014 Aluminum Alloy Bar, Rod, and Shapes; Rolled, Drawn, or Cold-Finished

Specification	AMS 4121 and AMS-QQ-A-225/4							AMS-QQ-A-225/4
Form	Bar, rod, and shapes, rolled, drawn, or cold-finished							
Temper	T6 and T651							T62[a]
Thickness, in.	Up to 1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000[b]	5.001-6.000[b]	6.001-8.000[b]	≤8.000[b]
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	65	65	65	65	65	65	65	65
LT	64[c]	63[c]	62[c]	61[c]	60[c]	59[c]	...	...
F_{ty}, ksi:								
L	55	55	55	55	55	55	55	55
LT	53[c]	52[c]	51[c]	50[c]	49[c]	48[c]	...	...
F_{cy}, ksi:								
L	53	53	53	53	53	53	53	...
LT	...	...	...	...	...	...	...	...
F_{su}, ksi	38	38	38	38	38	38	38	...
F_{bru}, ksi:								
(e/D = 1.5)	98	...	...	...	...	...	...	...
(e/D = 2.0)	124	...	...	...	...	...	...	...
F_{bry}, ksi:								
(e/D = 1.5)	77	...	...	...	...	...	...	...
(e/D = 2.0)	88	...	...	...	...	...	...	...
e, percent:								
L	8	8	8	8	8	8	8	8
E, 10^3 ksi	10.5							
E_c, 10^3 ksi	10.7							
G, 10^3 ksi	4.0							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.101							
C, K, and α	See Figure 3.2.1.0							

a Design allowables were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers.
b For square, rectangular, hexagonal, or octagonal bar, maximum thickness is 4 in., and maximum cross-sectional area is 36 sq. in.
c Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

Table 3.2.1.0(e). Design Mechanical and Physical Properties of 2014 Aluminum Alloy Die Forging

Specification	AMS 4133, AMS-A-22771, and AMS-QQ-A-367							AMS-A-22771 and AMS-QQ-A-367						
Form	Die forging													
Temper	T6[a]							T652						
Thickness[b], in.	≤ 1.000		1.001-2.000		2.001-3.000		3.001-4.000	≤ 1.000		1.001-2.000		2.001-3.000		3.001-4.000
Basis	A	B	A	B	A	B	S	A	B	A	B	A	B	S
Mechanical Properties:														
F_{tu}, ksi:														
L	65	67	65	67	65	67	63	65	67	65	67	65	67	63
T[c]	64[d]	...	64[d]	...	63[d]	...	63	64[d]	...	64[d]	...	63[d]	...	63
F_{ty}, ksi:														
L	56	59	56	59	55	58	55	56	59	56	59	55	58	55
T[c]	55[d]	...	55[d]	...	54[d]	...	54	55[d]	...	55[d]	...	54[d]	...	54
F_{cy}, ksi:														
L	59	62	59	62	58	61	58	56	59	56	59	55	58	55
ST	56	59	56	59	55	58	55	59	62	59	62	58	61	58
F_{su}, ksi	40	41	40	41	39	40	39	40	41	40	41	39	40	39
F_{bru}[e], ksi:														
(e/D = 1.5)	91	94	91	94	91	94	88	91	94	91	94	91	94	88
(e/D = 2.0)	123	127	123	127	123	127	120	123	127	123	127	123	127	120
F_{bry}[e], ksi:														
(e/D = 1.5)	73	77	73	77	71	75	71	73	77	73	77	71	75	71
(e/D = 2.0)	90	94	90	94	88	93	88	90	94	90	94	88	93	88
e, percent (S-basis):														
L	6	...	6	...	6	...	6	6	...	6	...	6	...	6
T[c]	3	...	2	...	2	...	2	3	...	2	...	2	...	2
E, 10^3 ksi	10.5													
E_c, 10^3 ksi	10.8													
G, 10^3 ksi	4.0													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.2.1.0													

a When die forgings are machined before heat treatment, the mechanical properties are applicable, provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.
b Thickness at time of heat treatment.
c T indicates any grain direction not within ±15° of being parallel to the forging flow lines. F_{cy}(T) values are based upon short transverse (ST) test data.
d Specification value. T tensile properties are presented on S basis only.
e Bearing values are “dry pin” values per Section 1.4.7.1.

Supercedes page 3-32 of MIL-HDBK-5H.

Table 3.2.1.0(f). Design Mechanical and Physical Properties of 2014 Aluminum Alloy Hand Forging

Specification	AMS 4133, AMS-A-22771, and AMS-QQ-A-367							AMS-A-22771 and AMS-QQ-A-367						
Form	Hand forging													
Temper	T6[a]							T652[b]						
Cross-Sectional Area, in.^{2}	≤ 256													
Thickness, in.	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	6.001-7.000	7.001-8.000	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	6.001-7.000	7.001-8.000
Basis	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:														
F_{tu}, ksi:														
L	65	64	63	62	61	60	59	65	64	63	62	61	60	59
LT	65	64	63	62	61	60	59	65	64	63	62	61	60	59
ST	...	62[c]	61[c]	60[c]	59[c]	58[c]	57[c]	...	62[c]	61[c]	60[c]	59[c]	58[c]	57[c]
F_{ty}, ksi:														
L	56	56	55	54	53	52	51	56	56	55	54	53	52	51
LT	56	55	55	54	53	52	51	56	55	55	54	53	52	51
ST	...	55[c]	54[c]	53[c]	53[c]	52[c]	51[c]	...	52[c]	51[c]	50[c]	50[c]	49[c]	48[c]
F_{cy}, ksi:														
L	56	56	55	54	53	...	...	56	56	55	54	53	...	...
LT	56	55	55	54	53	...	...	57	56	56	55	54	...	...
ST	...	...	...	...	...	...	...	...	57	56	55	55	...	...
F_{su}, ksi	40	39	39	38	38	...	...	38	37	37	36	36	...	...
F_{bru}, ksi:														
(e/D = 1.5)	91	90	88	87	85	...	...	88	87	85	84	83	...	...
(e/D = 2.0)	117	115	113	112	110	...	...	115	113	111	110	108	...	...
F_{bry}, ksi:														
(e/D = 1.5)	78	78	77	76	74	...	...	77	76	76	74	73	...	...
(e/D = 2.0)	90	90	88	87	85	...	...	91	89	89	87	86	...	...
e, percent:														
L	8	8	8	7	7	6	6	8	8	8	7	7	6	6
LT	3	3	3	2	2	2	2	3	3	3	2	2	2	2
ST	...	2	2	1	1	1	1	...	2	2	1	1	1	1
E, 10^3 ksi	10.5													
E_c, 10^3 ksi	10.8													
G, 10^3 ksi	4.0													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.2.1.0													

a When hand forgings are machined before heat treatment, the section thickness at time of heat treatment shall determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table.
b Bearing values are "dry pin" values per Section 1.4.7.1.
c Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

Table 3.2.1.0(g). Design Mechanical and Physical Properties of 2014 Aluminum Alloy Extrusion

Specification	AMS 4153 and AMS-QQ-A-200/2											AMS-QQ-A-200/2		
Form	Extruded bar, rod, and shapes													
Temper	T6, T6510, and T6511											T62[a]		
Cross-Sectional Area, in.^{2}	≤25										>25-≤32	All	≤25	>25-≤32
Thickness or Dia., in.[b]	0.125-0.499		0.500-0.749		0.750-1.499		1.500-1.750		1.751-2.999	3.000-4.499	≥0.750	≤0.749	≥0.750	≥0.750
Basis	A	B	A	B	A	B	A	B	S	S	S	S	S	S
Mechanical Properties:														
F_{tu}, ksi:														
L	60	62	64	68	68	70	68	71	68	68	68	60	60	60
LT (S-basis)	60[c]	...	64[c]	...	63[c]	...	61[c]	...	61	58	56	...	...	...
F_{ty}, ksi:														
L	53	57	58	62	60	63	60	63	60	60	58	53	53	53
LT (S-basis)	53[c]	...	55[c]	...	54[c]	...	52[c]	...	52	49	47	...	...	...
F_{cy}, ksi:														
L	52	56	57	61	59	62	59	62	...	...	...	...	...	...
LT	...	...	...	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	35	36	37	39	39	41	39	41	...	...	...	...	...	...
F_{bru}[d], ksi:														
(e/D = 1.5)	90	93	96	102	102	105	102	106	...	...	...	...	...	...
(e/D = 2.0)	116	120	124	132	132	136	132	138	...	...	...	...	...	...
F_{bry}[d], ksi:														
(e/D = 1.5)	73	78	80	85	82	86	82	86	...	...	...	...	...	...
(e/D = 2.0)	85	91	93	99	96	101	96	101	...	...	...	...	...	...
e, percent (S-basis):														
L	7	...	7	...	7	...	7	...	7	7	6	7	7	6
LT	5[e]	...	5	...	2	...	2	...	2	1	1	...	...	...
E, 10^3 ksi	10.8													
E_c, 10^3 ksi	11.0													
G, 10^3 ksi	4.1													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.2.1.0													

a Design allowables were based upon data obtained from testing samples of material, supplied in O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers.
b The mechanical properties are to be based upon the thickness at the time of quench.
c S-basis.
d Bearing values are “dry pin” values per Section 1.4.7.1.
e For 0.375-0.499 in.

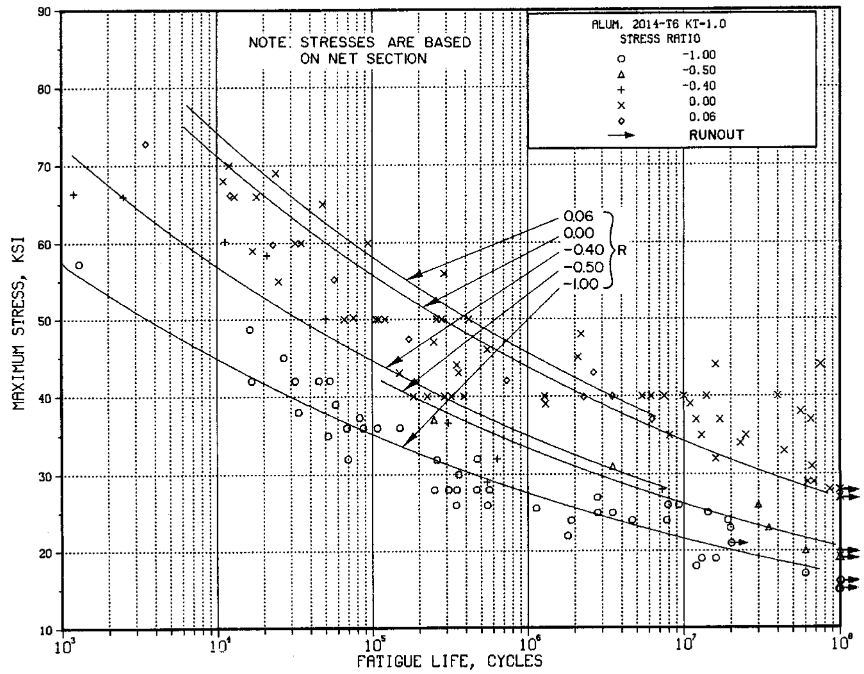

Figure 3.2.1.1.8(a). Best-fit S/N curves for unnotched 2014-T6 aluminum alloy, various wrought products, longitudinal direction.

Correlative Information for Figure 3.2.1.1.8(a)

Product Form: Drawn rod, 3/4-inch diameter
Rolled bar, 1 x 7-1/2-inch and 1-1/8-inch diameter
Rolled rod, 4-1/2-inch diameter
Extruded rod, 1-1/4-inch diameter
Extruded bar, 1-1/4 x 4 inch
Hand forging, 3 x 6 inch
Die forging, 4-1/2-inch diameter
Forged slab, 7/8-inch

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	67-78	60-72	RT

Specimen Details: Unnotched

Gross Diameter, inches	Net Diameter, inches
1.00	0.400
0.273	0.100
---	0.200
---	0.160
1.00	0.500

Surface Condition:
Mechanically polished and as-machined

References: 3.2.1.1.8(a), (b), (d), and (e)

Test Parameters:
Loading - Axial
Frequency - 1100 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 21.49-9.44 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.67}$
Standard Error of Estimate = 0.51
Standard Deviation in Life = 1.25
R^2 = 83%

Sample Size = 127

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

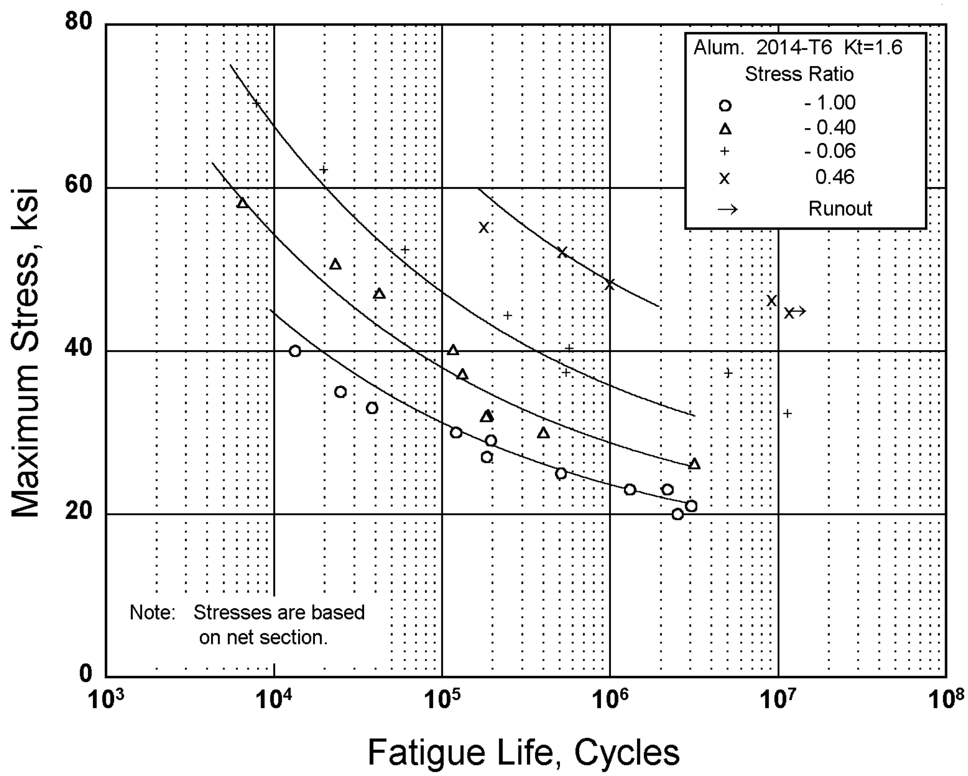

Figure 3.2.1.1.8(b). Best-fit S/N curves for notched, K_t = 1.6, 2014-T6 aluminum alloy rolled bar, longitudinal direction.

Correlative Information for Figure 3.2.1.1.8(b)

Product Form: Rolled bar, 1-1/8-inch diameter

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	72	64	RT

Specimen Details: Semicircular circumferential notch, K_t = 1.6
0.45-inch gross diameter
0.4-inch net diameter
0.01-inch root radius
60° flank angle, ω

Surface Condition: Polished

Reference: 3.2.1.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 10.65-4.02 log (S_{eq}-20.2)
$S_{eq} = S_{max}$ $(1\text{-}R)^{0.55}$
Std. Error of Estimate, Log (Life) = 0.33
Standard Deviation, Log (Life) = 0.87
R^2 = 86%

Sample Size = 33

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

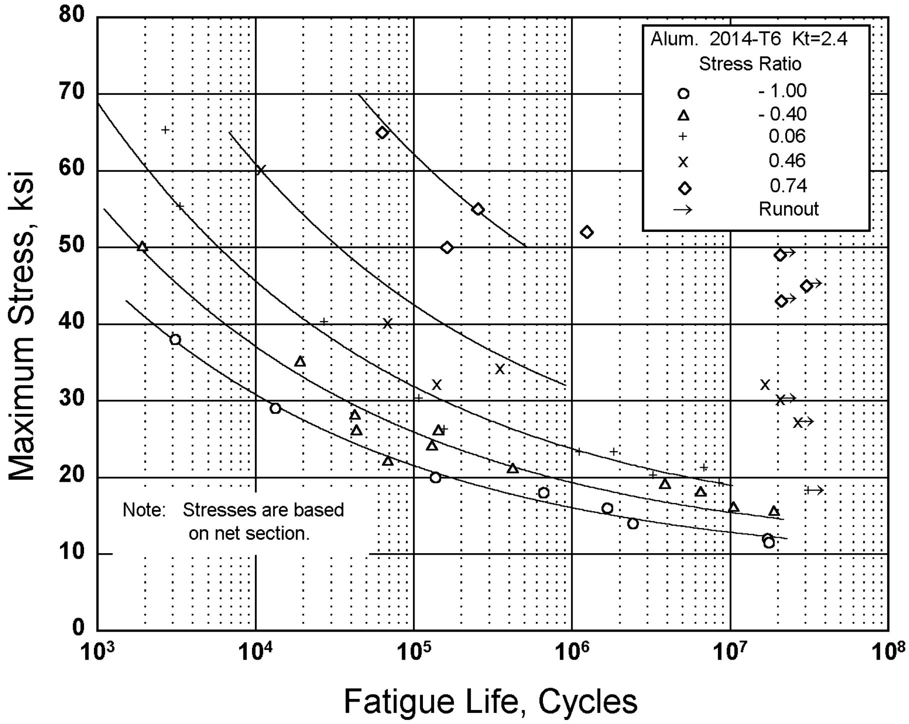

Figure 3.2.1.1.8(c). Best-fit S/N curves for notched, K_t = 2.4, 2014-T6 aluminum alloy rolled bar, longitudinal direction.

Correlative Information for Figure 3.2.1.1.8(c)

Product Form: Rolled bar, 1-1/8-inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
72	64	RT

Specimen Details: Circumferential V-notch, $K_t = 2.4$
0.500-inch gross diameter
0.400-inch net diameter
0.032-inch notch radius
60° flank angle, ω

Surface Condition: Polished

Reference: 3.2.1.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 10.59 - 4.36 \log (S_{eq} - 11.7)$
$S_{eq} = S_{max} (1-R)^{0.52}$
Std. Error of Estimate, Log (Life) = 0.38
Standard Deviation, Log (Life) = 1.18
$R^2 = 90\%$

Sample Size = 39

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

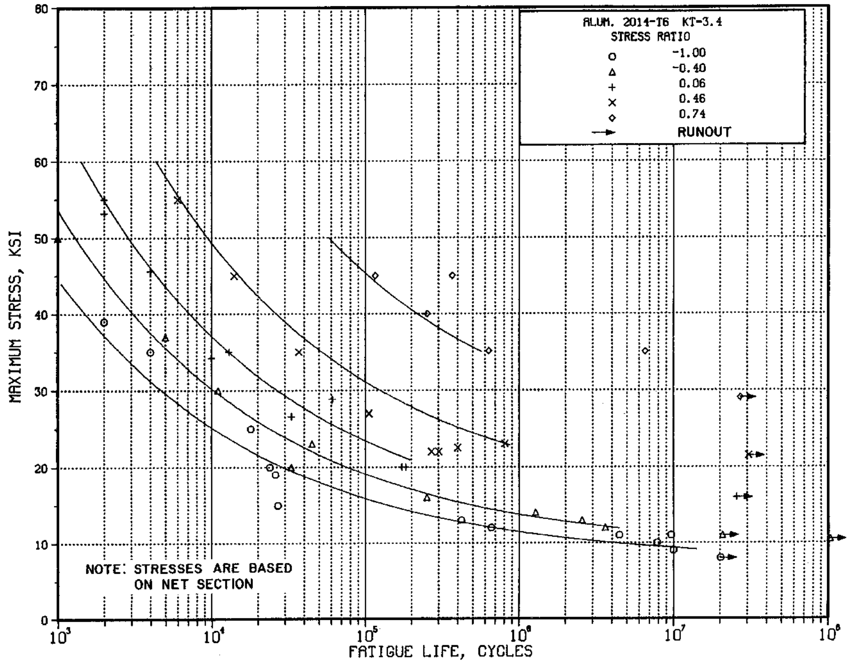

Figure 3.2.1.1.8(d). Best-fit S/N curves for notched, K_t = 3.4, 2014-T6 aluminum alloy rolled and extruded bar, longitudinal direction.

Correlative Information for Figure 3.2.1.1.8(d)

Product Form: Extruded bar, 1-1/8-inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
75	67	RT

Specimen Details: Circumferential V-notch, K_t = 3.4
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch notch radius
60° flank angle, ω

Surface Condition: Smooth machine finish

References: 3.2.1.1.8(b) and (c)

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\log N_f = 8.35 - 3.10 \log (S_{eq} - 10.6)$
$S_{eq} = S_{max} (1-R)^{0.52}$
Standard Error of Estimate = 0.34
Standard Deviation in Life = 1.10
R^2 = 90%

Sample Size = 45

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

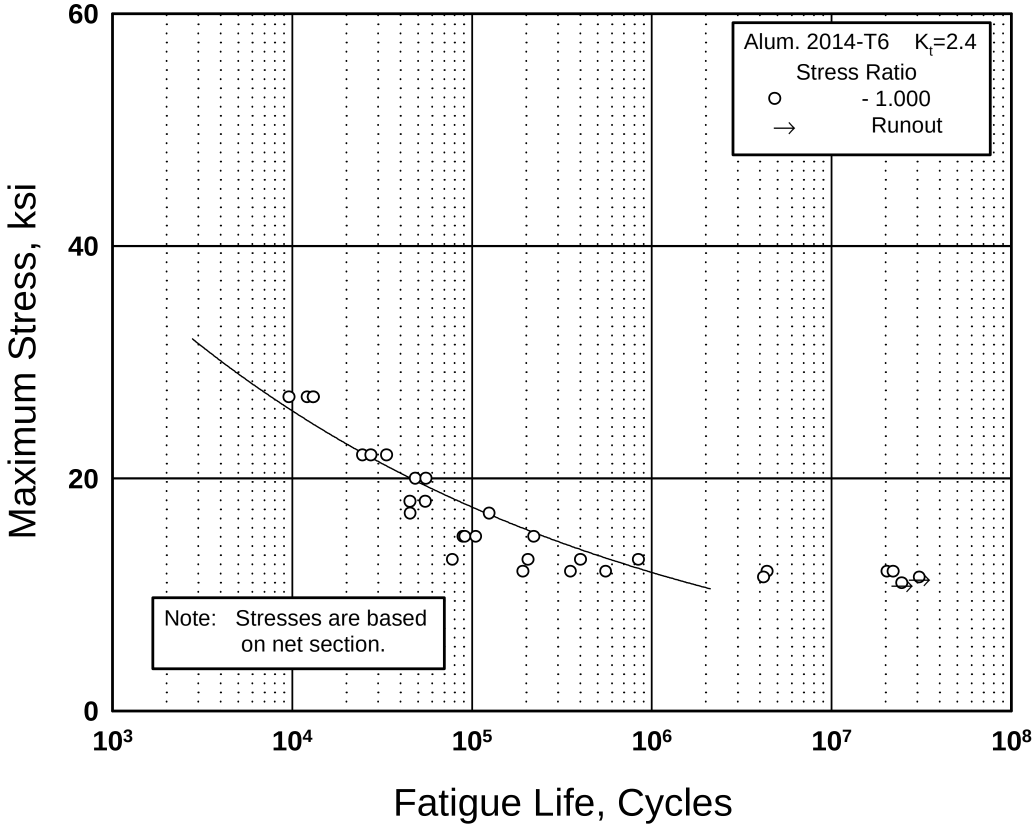

Figure 3.2.1.1.8(e). Best-fit S/N curves for notched, K_t = 2.4, 2014-T6 aluminum alloy hand forging, longitudinal and short transverse directions.

Correlative Information for Figure 3.2.1.1.8(e)

Product Form: Hand forging, 3 x 6 inch

Properties: TUS, ksi TYS, ksi Temp.,°F

Not specified RT

Specimen Details: Circumferential V-notch, K_t = 2.4
0.273-inch gross diameter
0.100-inch net diameter
0.010-inch notch radius
60° flank angle, ω

Surface Condition: Mechanically polished

Reference: 3.2.1.1.8(d)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Maximum Stress Equation:
Log N_f = 12.4-5.95 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.53
Standard Deviation, Log (Life) = 0.91
R^2 = 66%

Sample Size = 28

3.2.2 2017 ALLOY

3.2.2.0 *Comments and Properties* — 2017 is a heat-treatable Al-Cu alloy available in the form of rolled bar, rod, and wire, and is used principally for fasteners. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification for 2017 aluminum alloy is presented in Table 3.2.2.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.2.0(b). Figure 3.2.2.0 shows the effect of temperature on thermal expansion.

Table 3.2.2.0(a). Material Specifications for 2017 Aluminum Alloy

Specification	Form
AMS-QQ-A-225/5	Rolled bar and rod
AMS 4118	Bar and rod, rolled or cold-finished

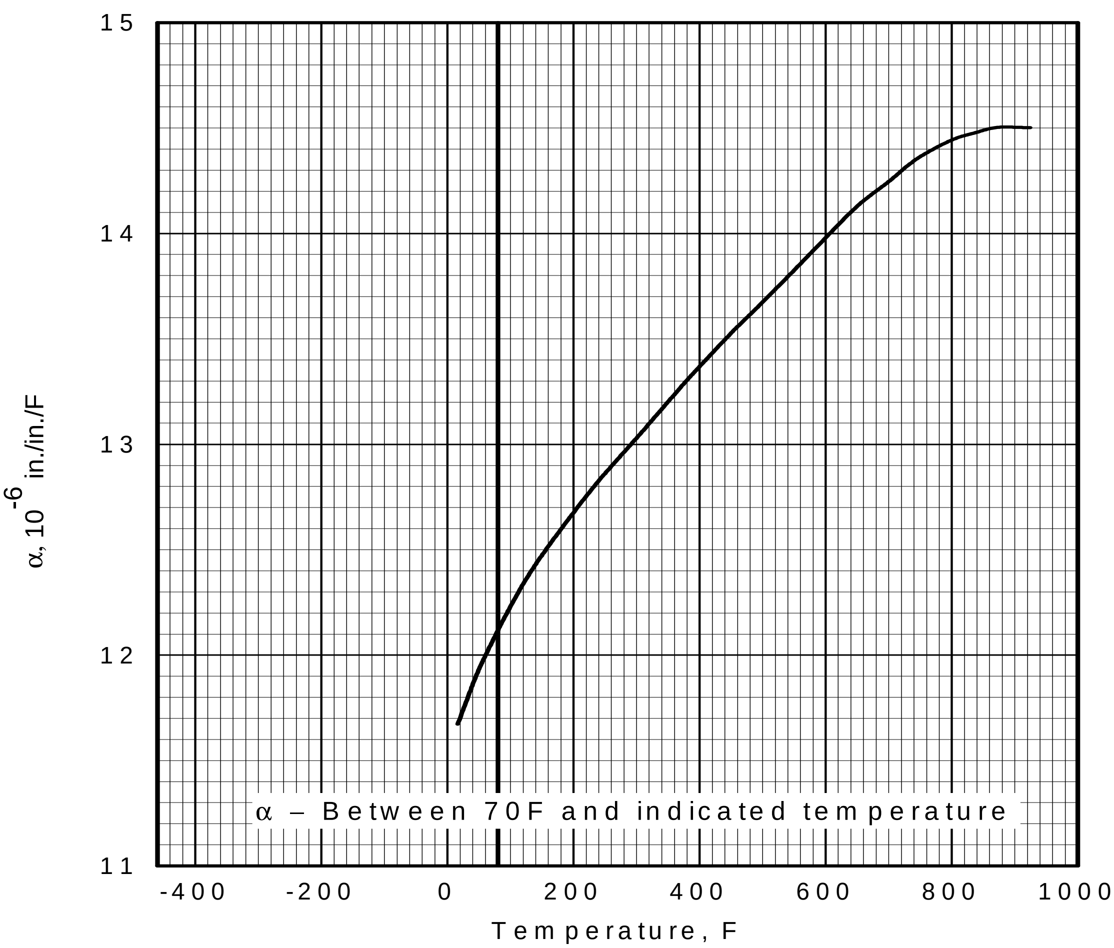

Figure 3.2.2.0. Effect of temperature on the thermal expansion of 2017 aluminum alloy.

3.2.3 2024 ALLOY

3.2.3.0 *Comments and Properties* — 2024 is a heat-treatable Al-Cu alloy which is available in a wide variety of product forms and tempers. The properties vary markedly with temper; those in T3 and T4 type tempers are noteworthy for their high toughness, while T6 and T8 type tempers have very high strength. This alloy has excellent properties and creep resistance at elevated temperatures. The T6 and T8 type tempers have very high resistance to corrosion. However, as shown in Table 3.1.2.3.1(a), 2024-T3, -T4, and -T42 rolled plate, rod and bar, and extruded shapes and 2024-T6 and -T62 forgings have a 'D' SCC rating. This is the lowest rating and means that SCC failures have occurred in service or would be anticipated if there is any sustained stress. In-service failures are caused by stresses produced by any combination of sources including solution heat treatment, straightening, forming, fit-up, clamping, sustained service loads or high service compression stresses that produce residual tensile stresses. These stresses may be tension or compression as well as the stresses due to the Poisson effect, because the actual failures are caused by the resulting sustained shear stresses. Pin-hole flaws in corrosion protection are sufficient for SCC. The weldability of the alloy is discussed in Section 3.1.3.4.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 2024 are presented in Table 3.2.3.0(a). Room-temperature mechanical properties are shown in Tables 3.2.3.0(b) through (j_2). The effect of temperature on the physical properties of this alloy is shown in Figure 3.2.3.0.

Table 3.2.3.0(a). Material Specifications for 2024 Aluminum Alloy

Specification	Form
AMS 4037	Bare sheet and plate
AMS 4035	Bare sheet and plate
AMS-QQ-A-250/4	Bare sheet and plate
AMS-QQ-A-250/5	Clad sheet and plate
AMS 4120	Bar and rod, rolled or cold-finished
AMS-QQ-A-225/6	Rolled or drawn bar, rod, and wire
AMS 4086	Tubing, hydraulic, seamless, drawn
AMS-WW-T-700/3	Tubing
AMS 4152	Extrusion
AMS 4164	Extrusion
AMS 4165	Extrusion
AMS-QQ-A-200/3	Extruded bar, rod, and shapes

The following temper designations are more specifically described than in Table 3.1.2.:

T81—The applicable designation for 2024-T3 sheet artificially aged to the required strength level.

T361—Solution heat treated and naturally aged followed by cold rolling and natural aging treatment.

T861—Solution heat treated and naturally aged followed by cold rolling and artificial aging treatment.

T72—Solution heat treated and aged by user in accordance with AMS 2770 to provide high resistance to stress-corrosion cracking, applicable only to sheet.

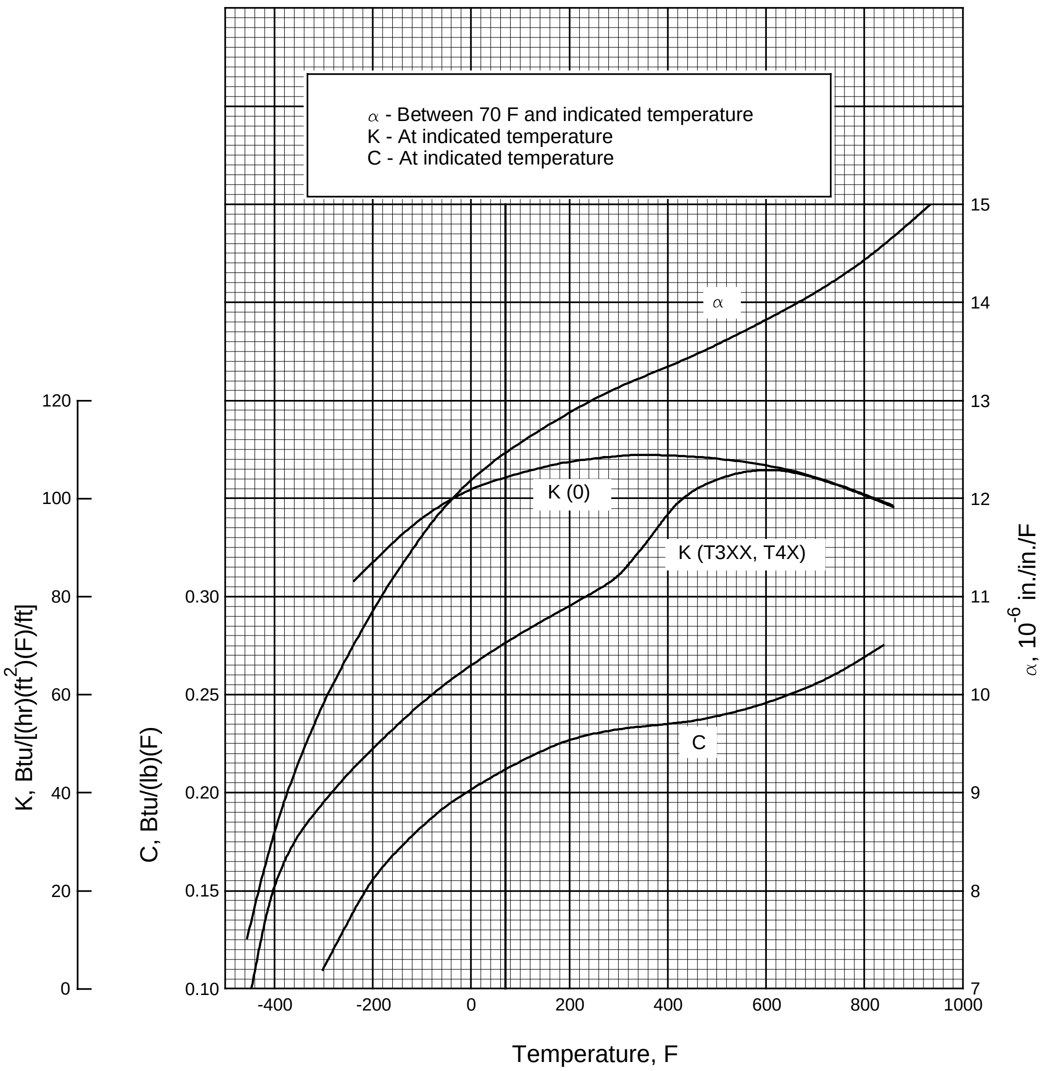

Figure 3.2.3.0. Effect of temperature on the physical properties of 2024 aluminum alloy.

The temper index for 2024 is as follows:

Section	Temper
3.2.3.1	T3, T351, T3510, T3511, T4, and T42
3.2.3.2	T361 (supersedes T36)
3.2.3.3	T62 and T72
3.2.3.4	T81, T851, T8510, and T8511
3.2.3.5	T861 (supersedes T86)

3.2.3.1 ***T3, T351, T3510, T3511, T4, and T42 Temper*** — Figures 3.2.3.1.1(a) through 3.2.3.1.5(b) present elevated temperature curves for various properties. Figures 3.2.3.1.6(a) through (q) present tensile and compressive stress-strain curves and tangent-modulus curves for various product forms and tempers at various temperatures. Figures 3.2.3.1.6(r) through (w) are full-range, stress-strain curves at room temperature for various product forms. Figures 3.2.3.1.8(a) through (i) provide S/N fatigue curves for unnotched and notched specimens for T3 and T4 tempers.

Table 3.2.3.0(b$_2$). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/4		AMS 4035 and AMS-QQ-A-250/4					AMS-QQ-A-250/4				
Form	Coiled Sheet		Flat Sheet and Plate									
Temper	T4		T42[a]					T62[a]				T72[a]
Thickness, in.	0.010-0.249		0.010-0.249	0.250-0.499	0.500-1.000	1.001-2.000	2.001-3.000	0.010-0.249	0.250-0.499	0.500-2.000	2.001-3.000	0.010-0.249
Basis	A	B	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:												
F_{tu}, ksi:												
L	62	64	62	62	61	60	...	63	63	63	...	...
LT	62	64	62	62	61	60	58	64	64	63	63	60
F_{ty}, ksi:												
L	40	42	38	38	38	38	...	50	50	50	...	...
LT	40	42	38	38	38	38	38	50	50	50	50	46
F_{cy}, ksi:												
L	40	42	42	42	40	37	...	52	52	52	...	...
LT	40	42	41	41	41	41	...	53	52	48	...	...
F_{su}, ksi	37	38	37	37	36	36	...	38	38	37	...	...
F_{bru}[b], ksi:												
(e/D = 1.5)	93	96	99	98	94	85[c]	...	103	103	102[c]	...	...
(e/D = 2.0)	118	122	123	123	121	119[c]	...	134	134	132[c]	...	...
F_{bry}[b], ksi:												
(e/D = 1.5)	56	59	67	67	67	67[c]	...	80	80	80[c]	...	...
(e/D = 2.0)	64	67	80	80	80	80[c]	...	95	95	95[c]	...	...
e, percent (S-basis):												
LT	[d]	...	[d]	12	8	[d]	4	5	5	5	5	5
E, 10^3 ksi	See Table 3.2.3.0(d)											
E_c, 10^3 ksi	See Table 3.2.3.0(d)											
G, 10^3 ksi	See Table 3.2.3.0(d)											
μ	See Table 3.2.3.0(d)											
Physical Properties:												
ω, lb/in.^{3}	0.100											
C, Btu/(lb)(°F)	See Figure 3.2.3.0											
K, Btu/[(hr)(ft^2)(°F)/ft]	71 (at 77°F) for T4X and 87 (at 77°F) for T6X, T7X, See Figure 3.2.3.0											
α, 10^{-6} in./in./°F	See Figure 3.2.3.0											

a Design allowables in some cases were based upon data obtained from testing samples of material, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be different than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.
b Bearing values are "dry pin" values per Section 1.4.7.1.
c See Table 3.1.2.1.1.
d See Table 3.2.3.0(c).

Table 3.2.3.0(b_3). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/4								
Form	Sheet		Plate				Sheet		Plate
Temper	T81		T851				T861		
Thickness, in.	0.010-0.249		0.250-0.499		0.500-1.000	1.001-1.499	0.020-0.062	0.063-0.249	0.250-0.500
Basis	A	B	A	B	S	S	S	S	S
Mechanical Properties:									
F_{tu}, ksi:									
L	67	68	67	68	66	66	71	72	70
LT	67	68	67	68	66	66	70	71	70
F_{ty}, ksi:									
L	59	61	58	60	58	57	63	67	64
LT	58	60	58	60	58	57	62	66	64
F_{cy}, ksi:									
L	59	61	58	60	58	56	63	67	64
LT	58	60	59	61	58	57	65	69	67
F_{su}, ksi	40	41	38	39	37	37	40	40	40
F_{bru}[a], ksi:									
(e/D = 1.5)	100	102	102	103	100	100[b]	108	110	108
(e/D = 2.0)	127	129	131	133	129	129[b]	140	142	140
F_{bry}[a], ksi:									
(e/D = 1.5)	83	86	86	89	86	85[b]	90	96	93
(e/D = 2.0)	94	97	101	105	101	99[b]	105	112	109
e, percent (S-basis):									
LT	5	...	5	...	5	5	3	4	4
E, 10^3 ksi	See Table 3.2.3.0(d)								
E_c, 10^3 ksi	See Table 3.2.3.0(d)								
G, 10^3 ksi	See Table 3.2.3.0(d)								
μ	See Table 3.2.3.0(d)								
Physical Properties:									
ω, lb/in.^{3}	0.100								
C, Btu/(lb)(°F)	See Figure 3.2.3.0								
K, Btu/[(hr)(ft^2)(°F)/ft]	87 (at 77°F)								
α, 10^{-6} in./in./°F	See Figure 3.2.3.0								

a Bearing values are "dry pin" values per Section 1.4.7.1.
b See Table 3.1.2.1.1.

Table 3.2.3.0(i$_1$). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Bar and Rod; Rolled, Drawn, or Cold-Finished

Specification	AMS 4120 and AMS-QQ-A-225/6							AMS-QQ-A-225/6
Form	Bar and rod; rolled, drawn, or cold-finished							
Temper	T351							T361
Thickness, in.	0.500-1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000[a]	5.001-6.000[a]	6.001-6.500[a]	≤0.375
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	62	62	62	62	62	62	62	69
LT	61[b]	59[b]	57[b]	55[b]	54[b]	52[b]	...	...
F_{ty}, ksi:								
L	45	45	45	45	45	45	45	52
LT	36[b]	36[b]	36[b]	36[b]	36[b]	36[b]	...	...
F_{cy}, ksi:								
L	34	34	34	34	34	34	...	...
LT	41	41	41	41	41	41	...	...
F_{su}, ksi	37	37	37	37	37	37	...	...
F_{bru}, ksi:								
(e/D = 1.5)	90	90	90	90	90	90	...	...
(e/D = 2.0)	115	115	115	115	115	115	...	...
F_{bry}, ksi:								
(e/D = 1.5)	63	63	63	63	63	63	...	...
(e/D = 2.0)	74	74	74	74	74	74	...	...
e, percent:								
L	10	10	10	10	10	10	10	10
E, 10^3 ksi	10.5							
E_c, 10^3 ksi	10.7							
G, 10^3 ksi	4.0							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.100							
C, K, and α	See Figure 3.2.3.0							

a For square, rectangular, hexagonal, or octagonal bar, minimum thickness is 4 inches, and maximum cross-sectional area is 36 square inches.

b Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

Table 3.2.3.0(i_2). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Bar and Rod; Rolled, Drawn, or Cold-Finished—Continued

Specification	AMS 4120 and AMS-QQ-A-225/6										AMS-QQ-A-225/6
Form	Bar and rod; rolled, drawn, or cold-finished										
Temper	T4[a]										T42[b]
Thickness, in.	0.125-0.499	0.500-1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-4.500[c]	4.501-5.000[d]	5.001-6.000[c]	6.001-6.500[d]	6.501-8.000[d]	≤6.500[c]
Basis	S	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:											
F_{tu}, ksi:											
L	62	62	62	62	62	62	62	62	62	58	62
LT	61[e]	61[e]	59[e]	57[e]	55[e]	54[e]	54[e]	52[e]	...	...	...
F_{ty}, ksi:											
L	45	42	42	42	42	42	40	40	40	38	40
LT	45[e]	42[e]	41[e]	40[e]	39[e]	39[e]	37[e]	36[e]	...	...	...
F_{cy}, ksi:											
L	36	33	33	33	33	33	32	32	...	...	...
LT	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	37	37	37	37	37	37	37	37	37	...	...
F_{bru}, ksi:											
(e/D = 1.5)	93	93	93	93	93	93	93	93	...	...	...
(e/D = 2.0)	118	118	118	118	118	118	118	118	...	...	...
F_{bry}, ksi:											
(e/D = 1.5)	63	59	59	59	59	59	56	56	...	...	...
(e/D = 2.0)	72	67	67	67	67	67	64	64	...	...	...
e, percent:											
L	10	10	10	10	10	10	10	10	10	10	10
E, 10^3 ksi	10.5										
E_c, 10^3 ksi	10.7										
G, 10^3 ksi	4.0										
μ	0.33										
Physical Properties:											
ω, lb/in.^{3}	0.100										
C and α	See Figure 3.2.3.0										
K, Btu/[(hr)(ft^2)(°F)/ft]	71 (at 77°F) for T4X (See Figure 3.2.3.0)										

a The T4 temper is obsolete and should not be specified for new designs.
b These properties apply when samples of material supplied in the O or F temper are heat treated to demonstrate response to heat treatment. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.
c For square, rectangular, hexagonal, or octagonal bar, maximum thickness is 4 inches, and maximum cross-sectional area is 36 square inches.
d Applies to rod only.
e Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

Table 3.2.3.0(i_3). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Bar and Rod; Rolled, Drawn, or Cold-Finished—Continued

Specification	AMS-QQ-A-225/6		
Form	Bar and rod; rolled, drawn, or cold finished		
Temper	T6[a]	T62[b]	T851
Thickness,[c] in.	≤6.500	≤6.500	0.500-6.500
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	62	60	66
LT	...	...	...
F_{ty}, ksi:			
L	50	46	58
LT	...	...	...
F_{cy}, ksi:			
L	...	...	...
LT	...	...	...
F_{su}, ksi	...	...	...
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
e, percent:			
L	5	5	5
E, 10^3 ksi	10.5		
E_c, 10^3 ksi	10.7		
G, 10^3 ksi	4.0		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.100		
C and α	See Figure 3.2.3.0		
K, Btu/[(hr)(ft^2)(°F)/ft]	87 (at 77°F) for T6X and T8XX		

a The T6 temper is obsolete and should not be specified for new designs.
b These properties apply when samples of material supplied in the O or F temper are heat treated to demonstrate response to heat treatment. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.
c For square, rectangular, hexagonal, or octagonal bar, maximum thickness is 4 inches, and maximum cross-sectional area is 36 square inches.

Table 3.2.3.0(j$_1$). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Extrusion

Specification	AMS 4152, AMS 4164, AMS 4165, and AMS-QQ-A-200/3														AMS-QQ-A-200/3		
Form	Extruded bar, rod, and shapes																
Temper	T3, T3510, and T3511														T81, T8510, and T8511		
Thickness,[a] in.	≤0.249		0.250-0.499		0.500-0.749		0.750-1.499		1.500-2.999		3.000-4.499		1.500-2.999	3.000-4.499	0.050-0.249	0.250-1.499	1.500-4.500
Cross-Section Area, in.^{2}	≤20								≤25				>25 - ≤32		≤20		≤32
Basis	A	B	A	B	A	B	A	B	A	B	A	B	S	S	S	S	S
Mechanical Properties:																	
F_{tu}, ksi:																	
L	57	61	60	62	60	62	65	70	70	74	70	74	68	68	64	66	66
LT	54	58	56	57	54	56	56	60	55	58	54	57	53	52	64	64	61
F_{ty}, ksi:																	
L	42	47	44	47	44	47	46	54	52	54	52	54	48	48	56	58	58
LT	37	41	38	40	37	39	37	43	39	41	39	41	36	36	55	57	57
F_{cy}, ksi:																	
L	34	38	37	39	38	40	41	48	49	50	49	51	45	45	57	59	59
LT	41	45	41	44	40	43	40	47	42	44	41	43	39	38	57	59	59
F_{su}, ksi	29	31	31	32	30	31	33	35	34	36	33	35	33	32	35	36	36
F_{bru}[b], ksi:																	
(e/D = 1.5)	84	90	78	81	78	80	84	90	88	93	86	91	86	84	94	96	92
(e/D = 2.0)	108	114	98	101	97	101	105	113	111	118	109	115	108	106	123	123	117
F_{bry}[b], ksi:																	
(e/D = 1.5)	61	68	55	59	55	59	57	67	63	66	62	65	59	57	79	82	82
(e/D = 2.0)	71	79	67	71	67	71	69	81	77	80	75	78	71	69	93	96	96
e, percent (S-basis):																	
L	12	...	12	...	12	...	10	...	10	...	10	...	8	8	4	5	5
E, 10^3 ksi	10.8																
E_c, 10^3 ksi	11.0																
G, 10^3 ksi	4.1																
μ	0.33																
Physical Properties:																	
ω, lb/in.^{3}	0.100																
C, K, and α	See Figure 3.2.3.0																

a The mechanical properties are to be based upon the thickness at the time of quench.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Supersedes page 3-84 of MIL-HDBK-5H

Table 3.2.3.0(j_2). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Extrusion—Continued

Specification	AMS-QQ-A-200/3									
Form	Extruded bar, rod, and shapes									
Temper	T42[a]									
Cross-Sectional Area, in.^{2}	≤ 25									
Thickness or Diameter,[b] in.	≤ 0.249	0.250-0.499	0.500-0.749	0.750-0.999	1.000-1.249	1.250-1.499	1.500-1.749	1.750-1.999	2.000-2.249	2.250-2.499
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	57	57	57	57	57	57	57	57	57	57
LT	55	54	52	51	49	47	45	43	41	39
F_{ty}, ksi:										
L	38	38	38	38	38	38	38	38	38	38
LT	36	35	34	33	32	31	30	29	28	27
F_{cy}, ksi:										
L	38	38	38	38	38	38	38	38	38	38
LT	39	38	37	36	35	34	33	31	30	29
F_{su}, ksi	29	29	29	29	29	29	28	27	26	24
F_{bru}[c], ksi:										
(e/D = 1.5)	81	80	79	77	75	74	71	69	67	64
(e/D = 2.0)	99	98	97	95	93	91	89	86	83	81
F_{bry}[c], ksi:										
(e/D = 1.5)	56	55	53	51	49	47	44	41	39	36
(e/D = 2.0)	69	67	65	63	61	59	56	53	50	47
e, percent:										
L	12	12	12	10	10	10	10	10	10	10
E, 10^3 ksi	10.8									
E_c, 10^3 ksi	11.0									
G, 10^3 ksi	4.1									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.100									
C, K, and α	See Figure 3.2.3.0									

a Design allowables were based upon data obtained from testing samples of material supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.
b The mechanical properties are to be based upon the thickness at the time of quench.
c Bearing values are "dry pin" values per Section 1.4.7.1.

Supersedes page 3-85 of MIL-HDBK-5H

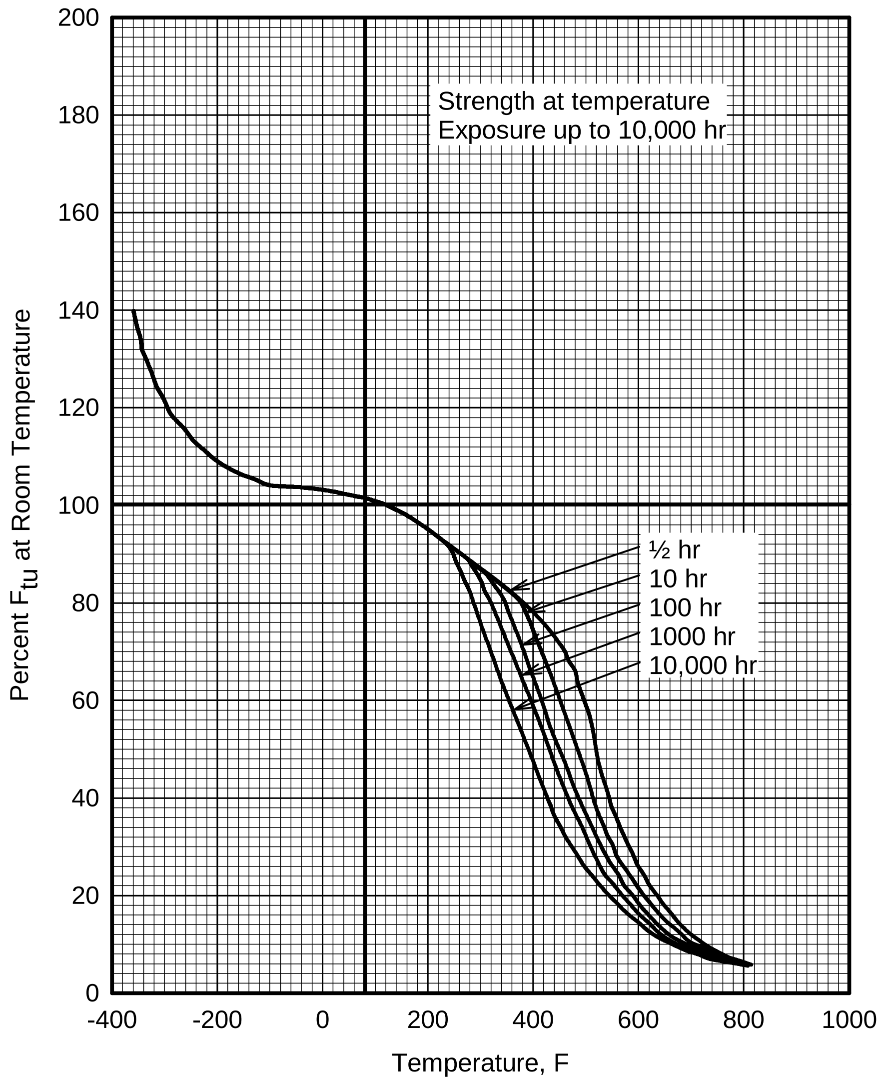

Figure 3.2.3.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2024-T3, T351, and 2024-T4 aluminum alloy (all products except extrusions).

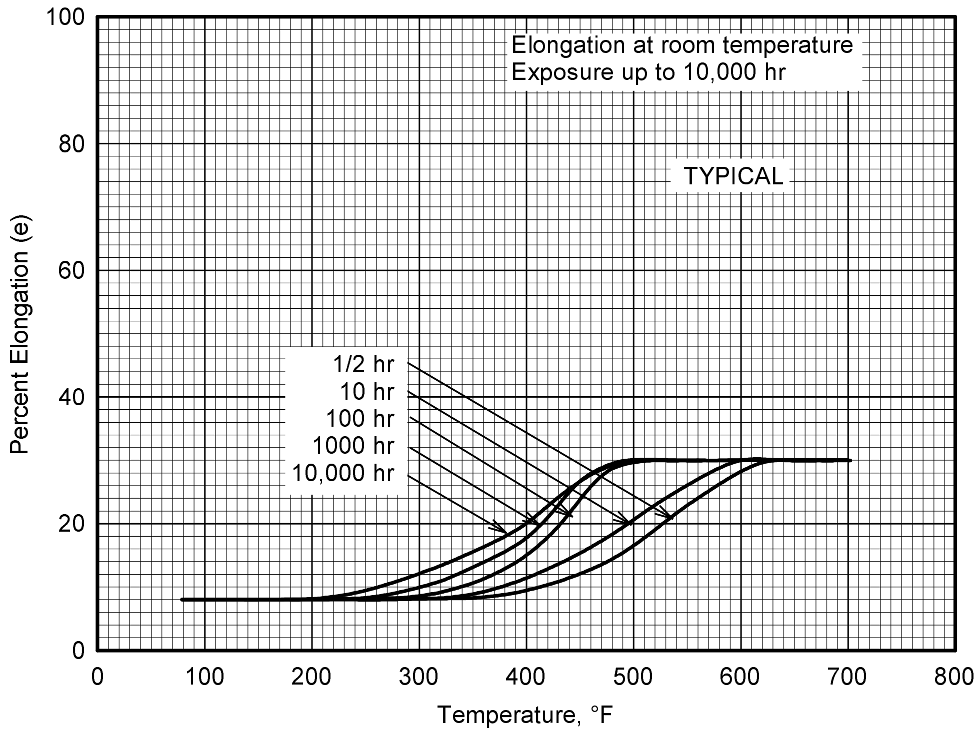

Figure 3.2.3.1.5(b). Effect of exposure at elevated temperature on the elongation (e) of 2024-T3, T351, T3510, T3511, T4, and T42 aluminum alloy (all products except thick extrusions).

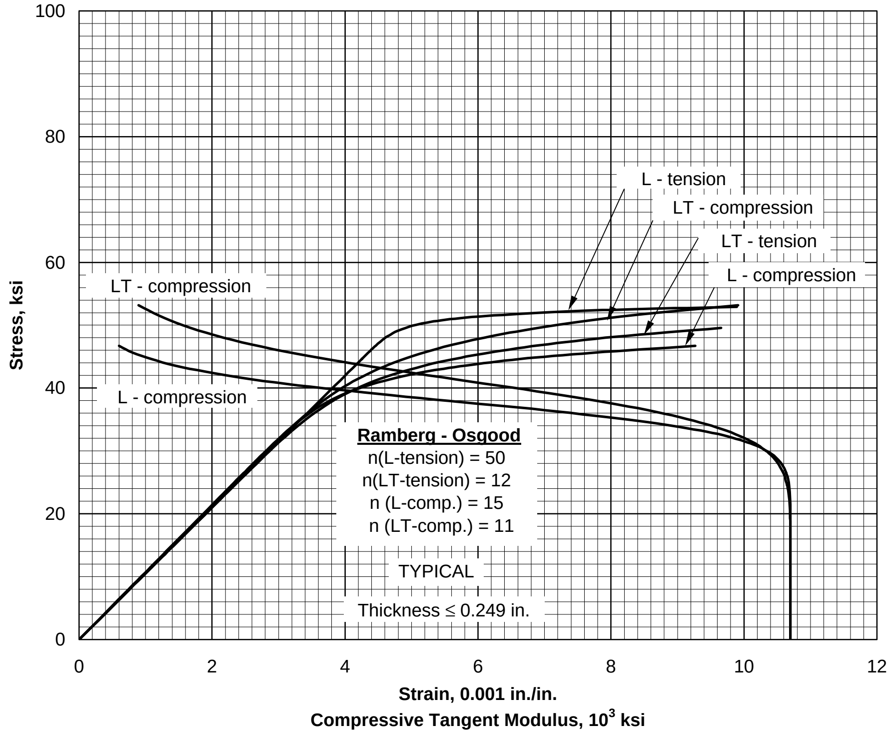

Figure 3.2.3.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy sheet at room temperature.

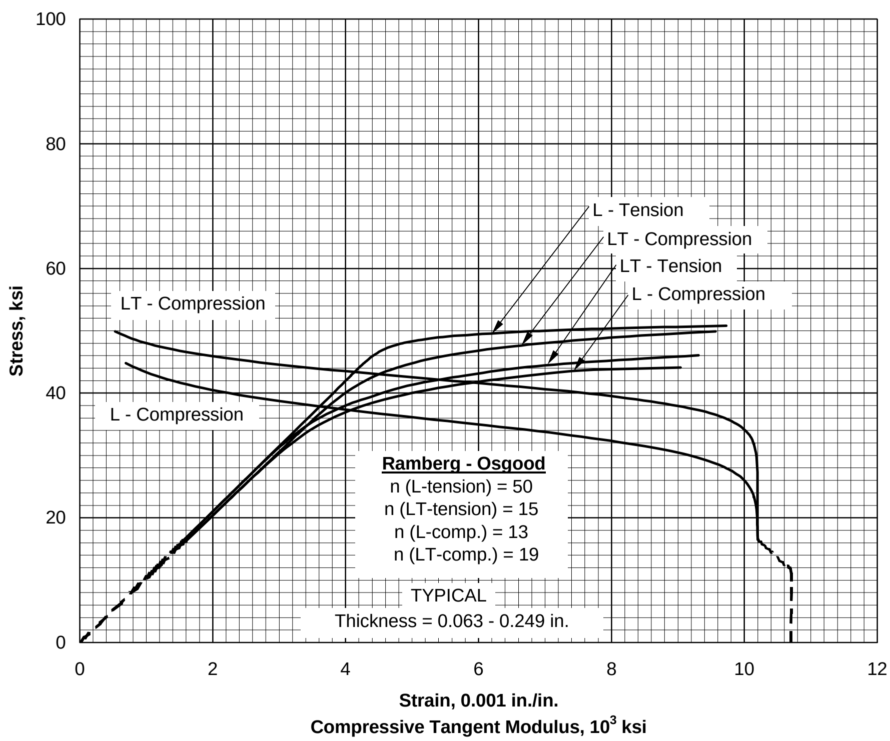

Figure 3.2.3.1.6(b). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at room temperature.

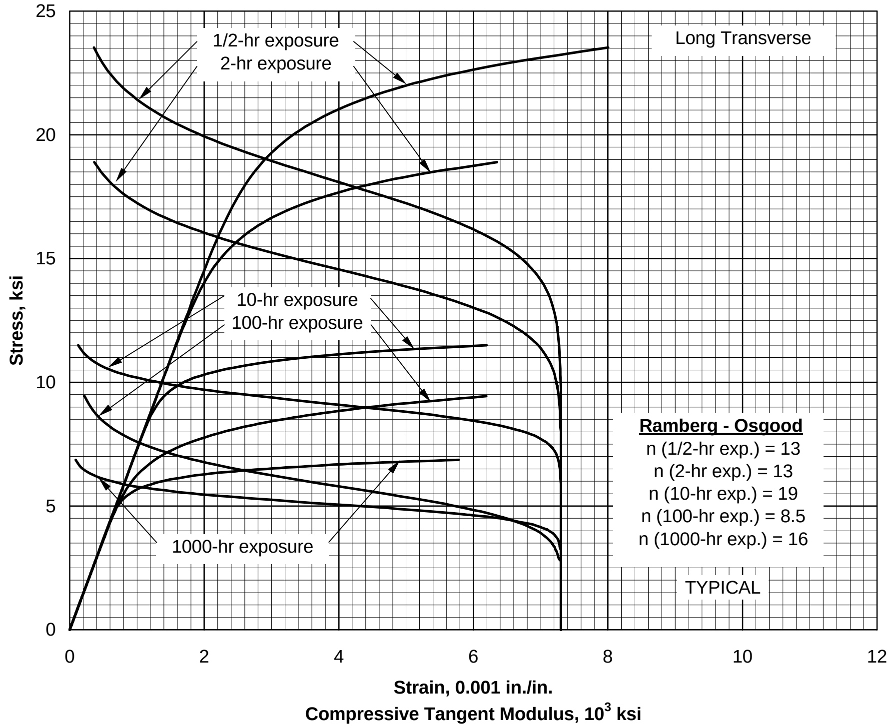

Figure 3.2.3.1.6(g). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 600°F.

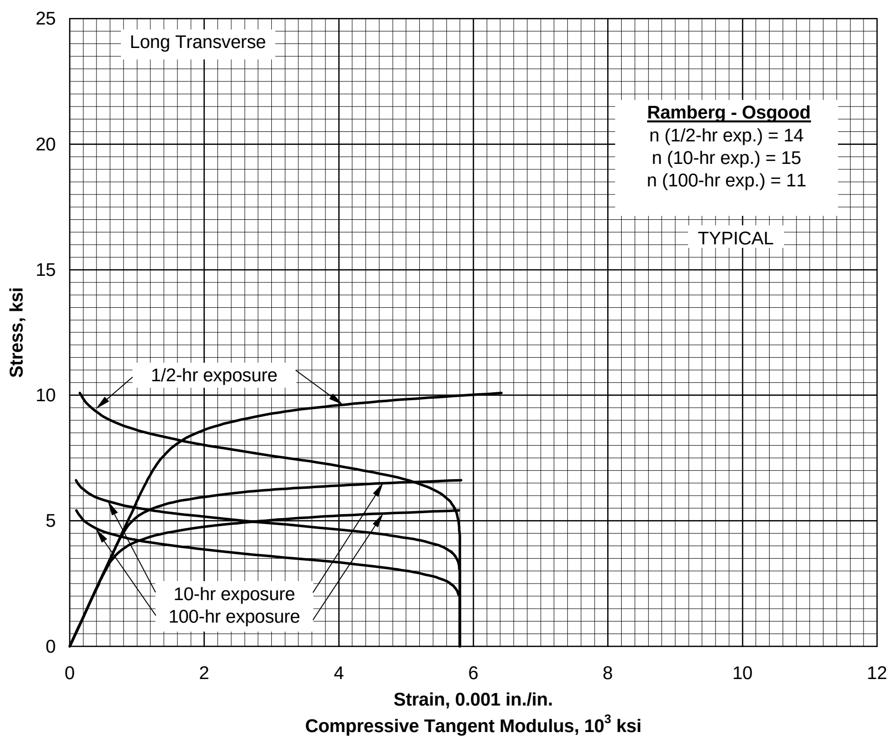

Figure 3.2.3.1.6(h). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T3 aluminum alloy sheet at 700°F.

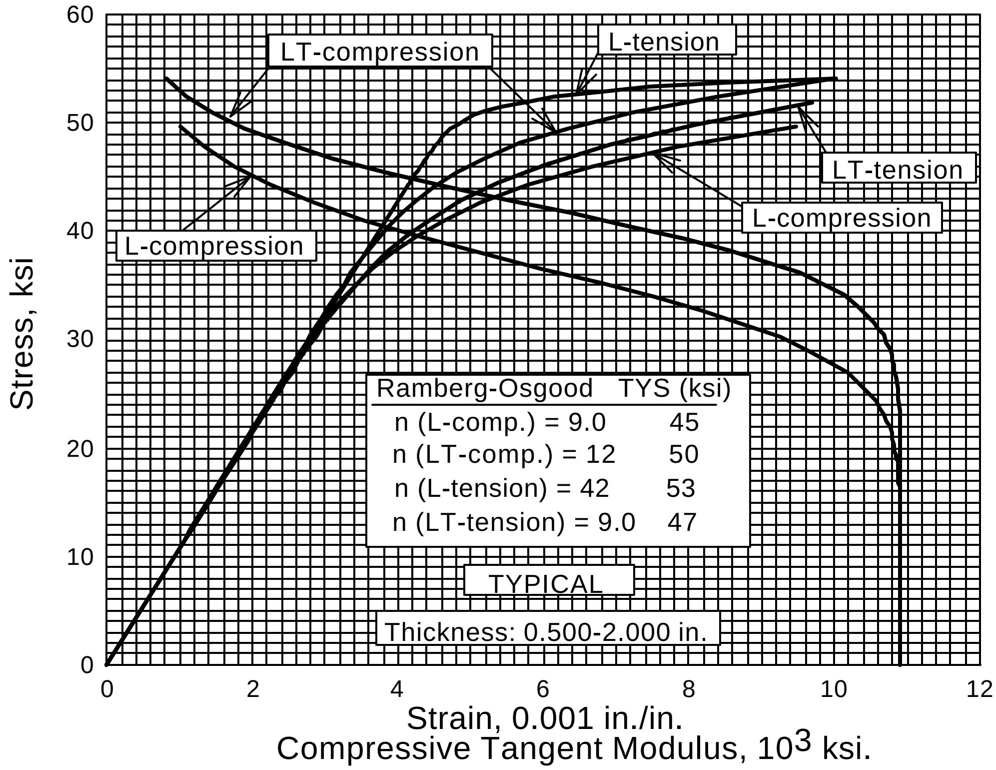

Figure 3.2.3.1.6(i). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T351 aluminum alloy plate at room temperature.

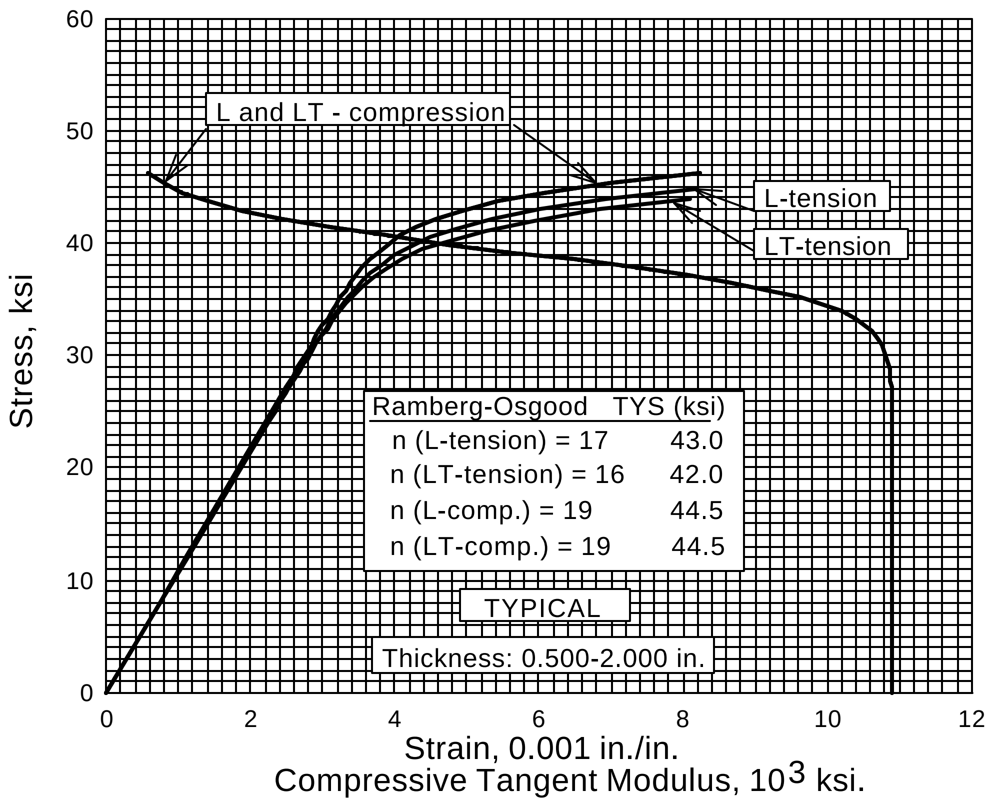

Figure 3.2.3.1.6(j). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T42 aluminum alloy plate at room temperature.

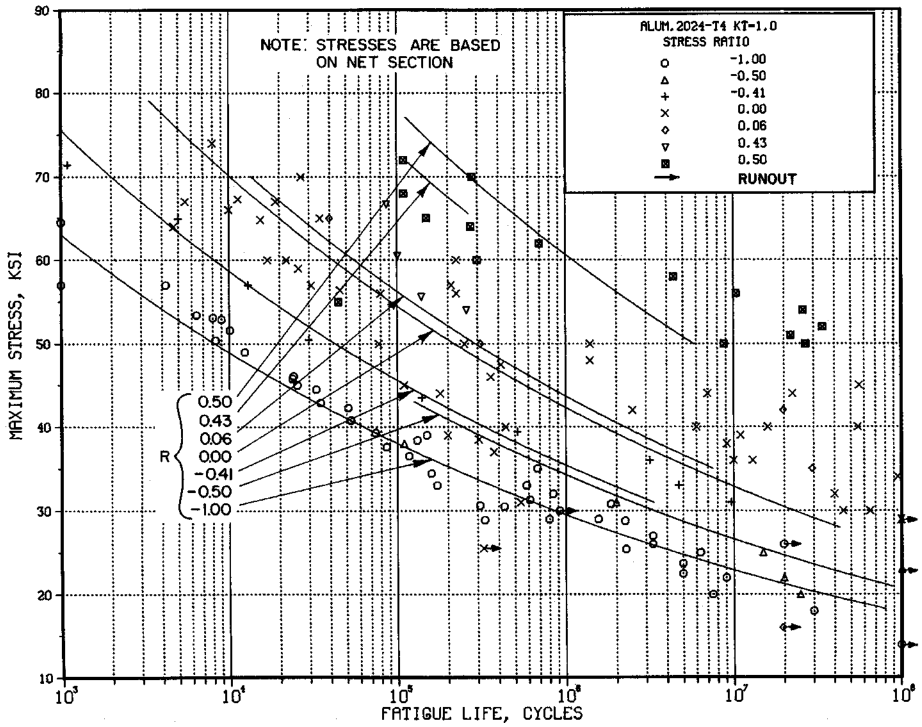

Figure 3.2.3.1.8(a). Best-fit S/N curves for unnotched 2024-T4 aluminum alloy, various wrought products, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(a)

Product Form: Rolled bar, 3/4 to 1/8 inch diameter
Drawn rod, 3/4-inch diameter
Extruded rod, 1-1/4-inch diameter
Extruded bar, 1-1/4 x 4-inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
69	45	RT (rolled)
71	44	RT (drawn)
85	65	RT (extruded)

Specimen Details: Unnotched
0.160 to 0.400-inch diameter

Surface Condition: Longitudinally polished

References: 3.2.1.1.8(a) through (c) and 3.2.3.1.8(i)

Test Parameters:
Loading - Axial
Frequency - 1800 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 20.83-9.09 log (S_{eq})
$S_{eq} = S_{max}\,(1-R)^{0.52}$
Standard Error of Estimate = 0.566
Standard Deviation in Life = 1.324
R^2 = 82%

Sample Size = 134

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

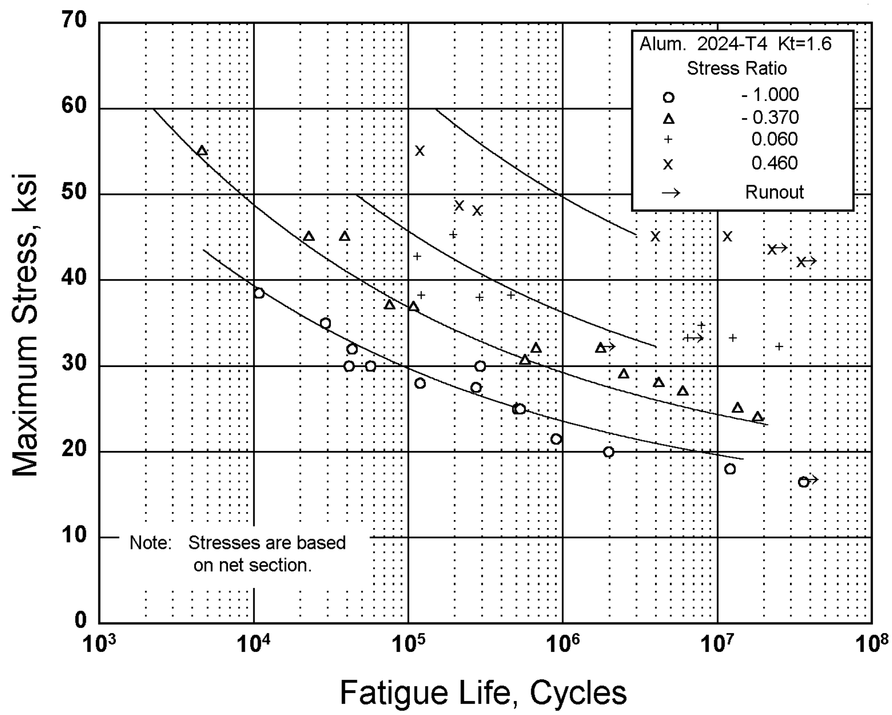

Figure 3.2.3.1.8(b). Best-fit S/N curves for notched, K_t = 1.6, 2024-T4 aluminum alloy bar, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(b)

Product Form: Rolled bar, 1-1/8-inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73	49	RT

Specimen Details: Semicircular
V-Groove, K_t = 1.6
0.450-inch gross diameter
0.400-inch net diameter
0.100-inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.1.1.8(a)

Test Parameters:
Loading - Axial
Frequency - 1800 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 12.25\text{-}5.16 \log (S_{eq}\text{-}18.7)$
$S_{eq} = S_{max} (1\text{-}R)^{0.57}$
Std. Error of Estimate, Log (Life) = 0.414
Standard Deviation, Log (Life) = 0.989
R^2 = 82%

Sample Size = 38

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

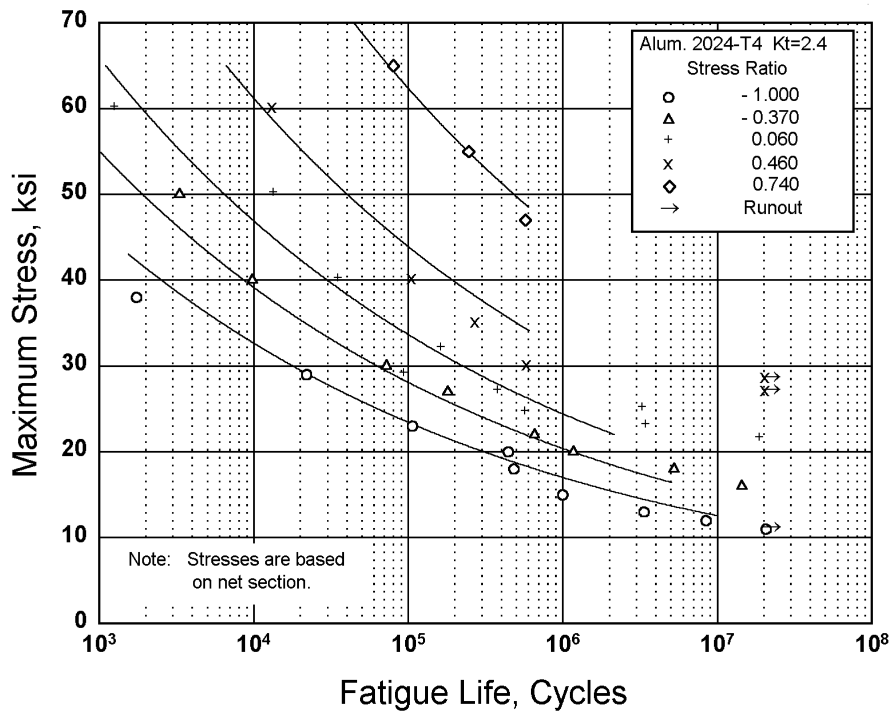

Figure 3.2.3.1.8(c). Best-fit S/N curves for notched, K_t = 2.4, 2024-T4 aluminum alloy bar, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(c)

Product Form: Rolled bar, 1-1/8-inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73	49	RT

Specimen Details: Circumferential
V-Groove, K_t = 2.4
0.500-inch gross diameter
0.400-inch net diameter
0.032-inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.1.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 1800 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 14.33-6.35 log (S_{eq}-3.2)
$S_{eq} = S_{max}$ (1-R)$^{0.48}$
Std. Error of Estimate, Log (Life) = 0.310
Standard Deviation, Log (Life) = 1.084
R^2 = 92%

Sample Size = 33

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

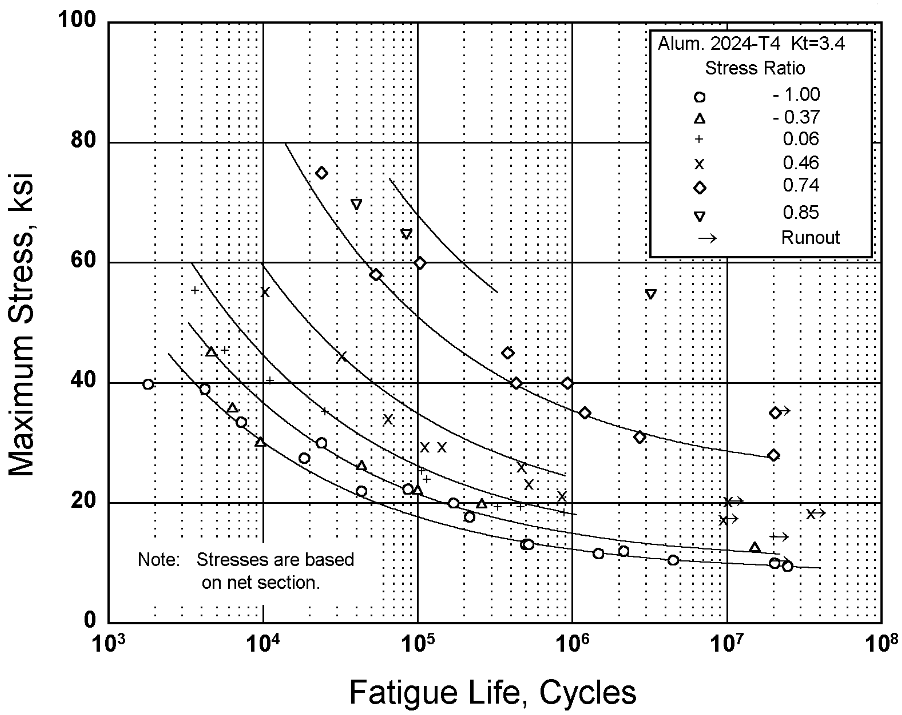

Figure 3.2.3.1.8(d). Best-fit S/N curves for notched, K_t = 3.4, 2024-T4 aluminum alloy, various wrought products, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(d)

Product Form: Rolled bar, 1-1/8-inch diameter
Extruded bar, 1-1/4-inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp., °F
74.2	—	RT (rolled)
84.1	—	RT (extruded)

Specimen Details: Circumferential
V-Groove, K_t = 3.4
0.450-inch gross diameter
0.400-inch net diameter
0.010-inch root radius, r
60° flank angle, ω

Surface Condition: As machined

References: 3.2.1.1.8(b) and (c)

Test Parameters:
Loading - Axial
Frequency - 1800 to 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\log N_f = 8.18-2.76 \log (S_{eq}-11.6)$
$S_{eq} = S_{max} (1-R)^{0.52}$
Std. Error of Estimate, Log (Life) = 0.292
Standard Deviation, Log (Life) = 1.011
R^2 = 92%

Sample Size = 51

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

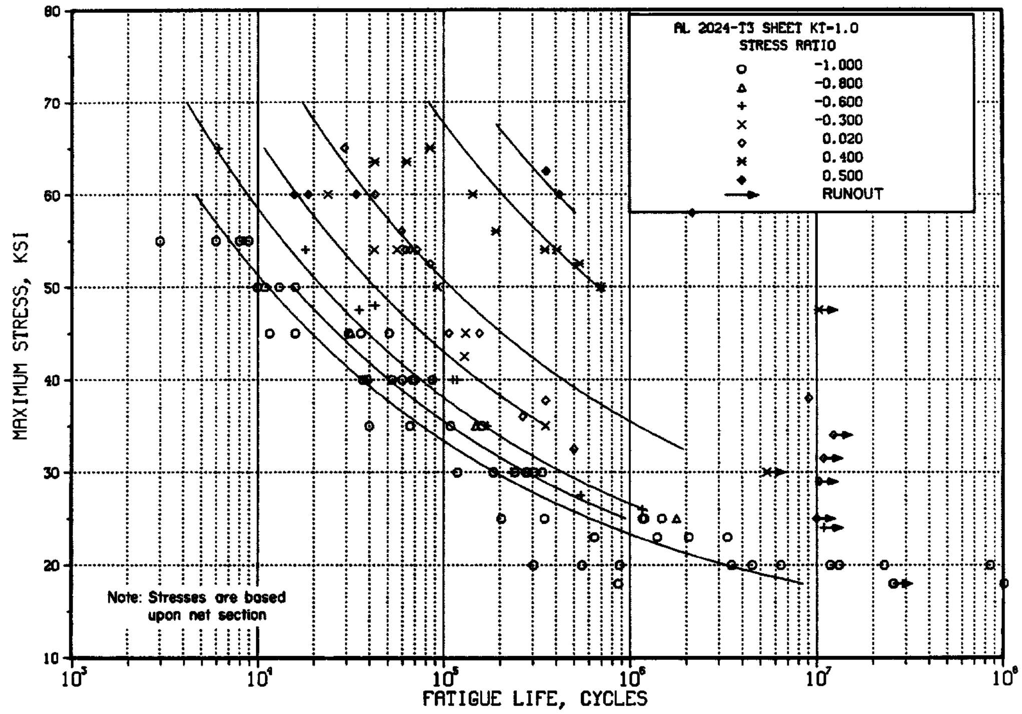

Figure 3.2.3.1.8(e). Best-fit S/N curves for unnotched, 2024-T3 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(e)

Product Form: Bare sheet, 0.090-inch

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	72, 73	52, 54	RT

Specimen Details: Unnotched
0.8 to 1.0-inch width

Surface Condition: Electropolished

References: 3.2.3.1.8(a) and (f)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1800 cpm

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 11.1\text{-}3.97 \log (S_{eq}\text{-}15.8)$
$S_{eq} = S_{max} (1\text{-}R)^{0.56}$
Standard Error of Estimate = 0.38
Standard Deviation in Life = 0.90
R^2 = 82%

Sample Size = 107

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

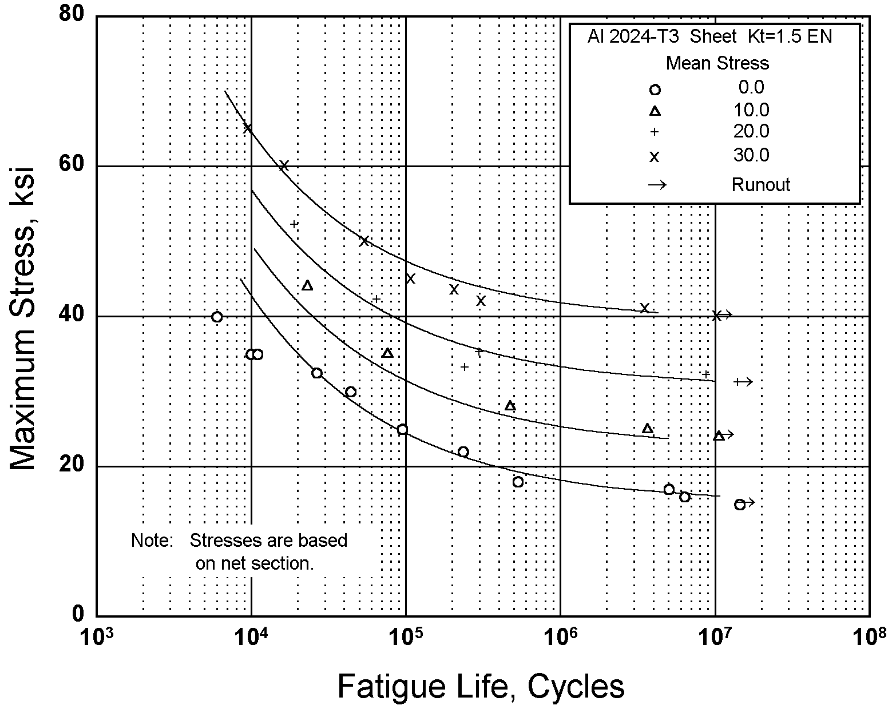

Figure 3.2.3.1.8(f). Best-fit S/N curves for notched, K_t = 1.5, 2024-T3 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(f)

Product Form: Bare sheet, 0.090-inch

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
73	54	RT (unnotched)
76	—	RT (notched K_t = 1.5)

Specimen Details: Edge notched, K_t = 1.5
3.00-inches gross width
1.500-inches net width
0.760-inch notch radius
0° flank angle

Surface Condition: Electropolished

Reference: 3.2.3.1.8(d)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 7.5-2.13 log (S_{eq}-23.7)
$S_{eq} = S_{max}\ (1\text{-}R)^{0.66}$
Std. Error of Estimate, Log (Life) = 0.30
Standard Deviation, Log (Life) = 0.95
R^2 = 90%

Sample Size = 26

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

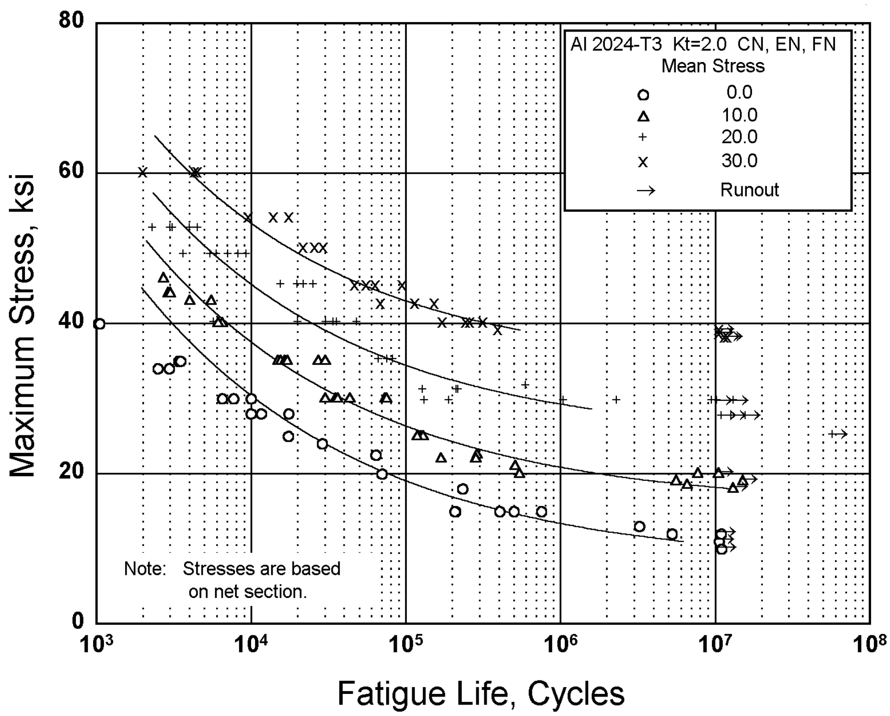

Figure 3.2.3.1.8(g). Best-fit S/N curves for notched, K_t = 2.0, 2024-T3 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(g)

Product Form: Bare sheet, 0.090-inch

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
73	54	RT (unnotched)
73	—	RT (notched K_t= 2.0)

Specimen Details: Notched, K_t = 2.0

Notch Type	Gross Width	Net Width	Notch Radius
Center	4.50	1.50	1.50
Edge	2.25	1.50	0.3175
Fillet	2.25	1.50	0.1736

Surface Condition: Electropolished, machined and burrs removed with fine crocus cloth

References: 3.2.3.1.8(b) and (f)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 9.2\text{-}3.33 \log (S_{eq}\text{-}12.3)$
$S_{eq} = S_{max} (1\text{-}R)^{0.68}$
Std. Error of Estimate, Log (Life) = 0.27
Standard Deviation, Log (Life) = 0.89
R^2 = 91%

Sample Size = 113

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

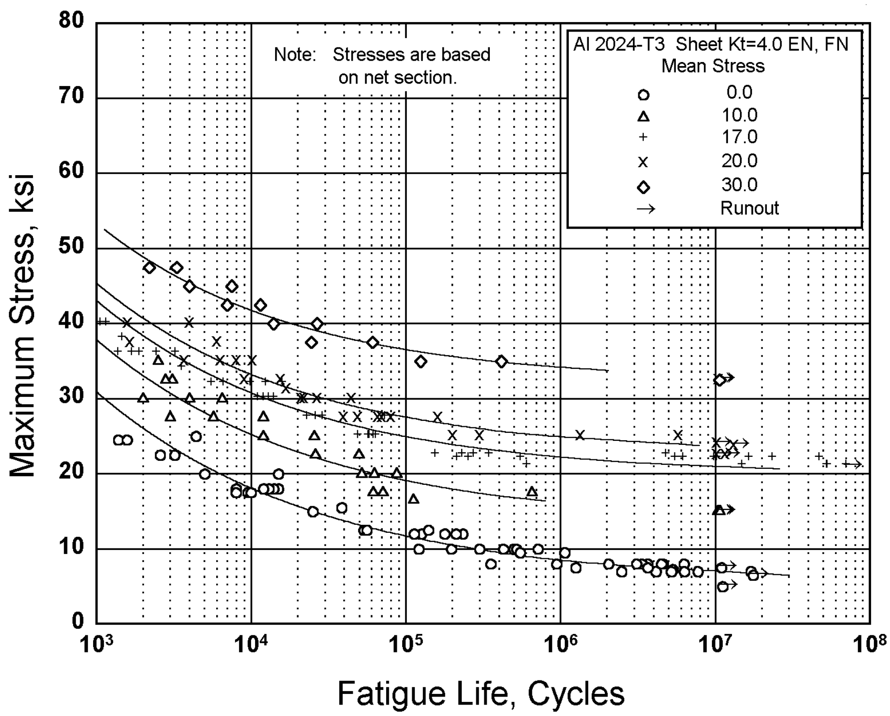

Figure 3.2.3.1.8(h). Best-fit S/N curves for notched, K_t = 4.0 of 2024-T3 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.2.3.1.8(h)

Product Form: Bare sheet, 0.090-inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
73	54	RT (unnotched)
67	—	RT (notched K_t = 2.0)

Specimen Details: Notched, K_t = 2.0

Notch Type	Gross Width	Net Width	Notch Radius
Center	2.25	1.50	0.057
Edge	4.10	1.50	0.070
Fillet	2.25	1.50	0.0195

Surface Condition: Electropolished, machined, and burrs removed with fine crocus cloth

References: 3.2.3.1.8(b), (e), (f), (g), and (h)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 8.3\text{-}3.30 \log (S_{eq}\text{-}8.5)$
$S_{eq} = S_{max} (1\text{-}R)^{0.66}$
Std. Error of Estimate, Log (Life) = 0.39
Standard Deviation, Log (Life) = 1.24
R^2 = 90%

Sample Size = 126

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

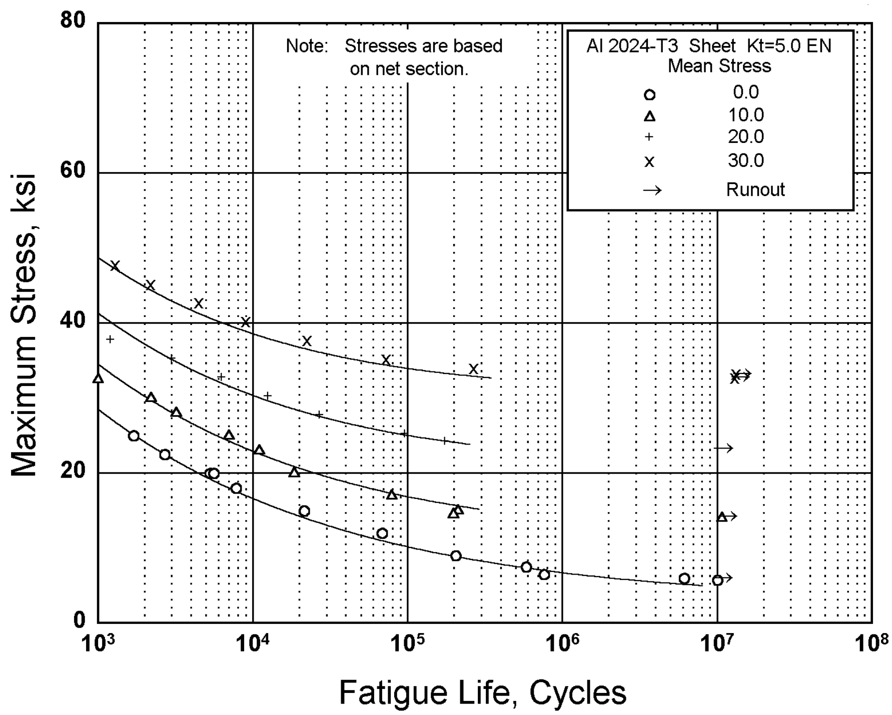

Figure 3.2.3.1.8(i). Best-fit S/N curves for notched, K_t = 5.0, 2024-T3 aluminum alloy sheet, longitudinal direction.

<u>Correlative Information for Figure 3.2.3.1.8(i)</u>

<u>Product Form</u>: Bare sheet, 0.090-inch

<u>Properties</u>:

TUS, ksi	TYS, ksi	Temp.,EF
73	54	RT (unnotched)
62	—	RT (notched K_t = 5.0)

<u>Specimen Details</u>: Edge notched, K_t = 5.0
2.25-inch gross width
1.500-inch net width
0.03125-inch notch radius
0E flank angle

<u>Surface Condition</u>: Electropolished

<u>Reference</u>: 3.2.3.1.8(c)

<u>Test Parameters:</u>
Loading - Axial
Frequency - 1100 to 1800 cpm
Temperature - RT
Environment - Air

<u>No. of Heats/Lots</u>: Not specified

<u>Equivalent Stress Equation</u>:
Log N_f = 8.9-3.73 log (S_{eq}-3.9)
$S_{eq} = S_{max}$ $(1\text{-}R)^{0.56}$
Std. Error of Estimate, Log (Life) = 0.39
Standard Deviation, Log (Life) = 1.24
R^2 = 90%

<u>Sample Size</u> = 35

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

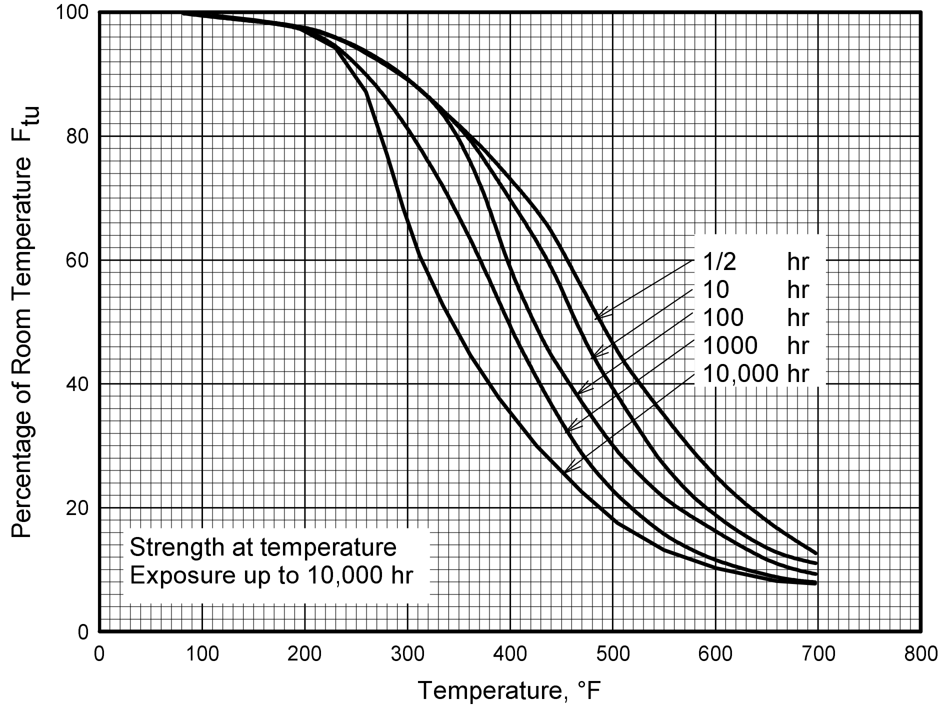

Figure 3.2.3.3.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2024-T62 aluminum alloy (all products).

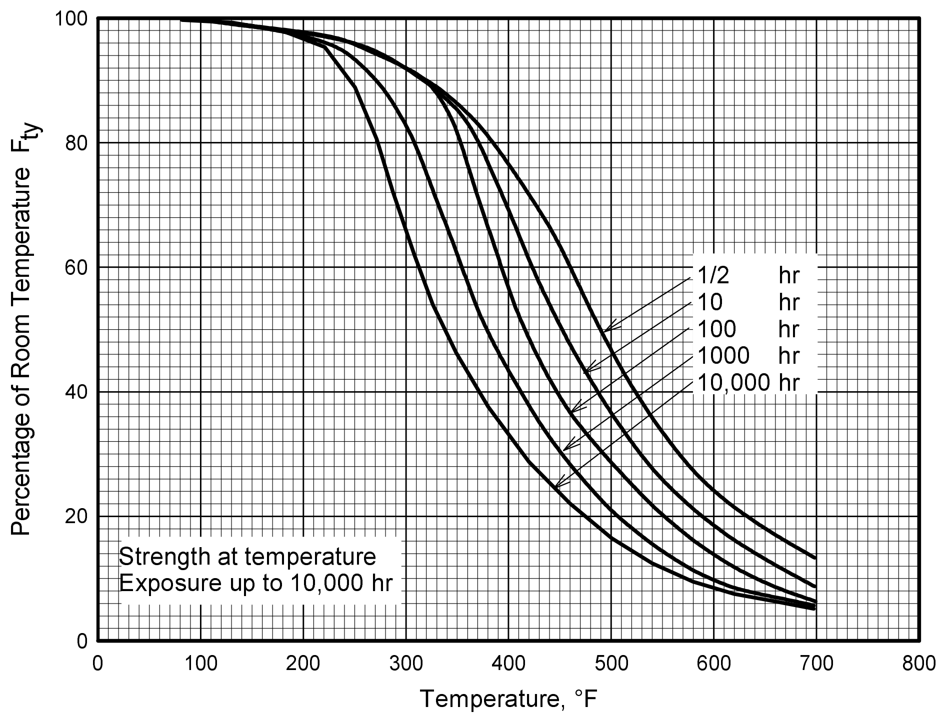

Figure 3.2.3.3.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T62 aluminum alloy (all products).

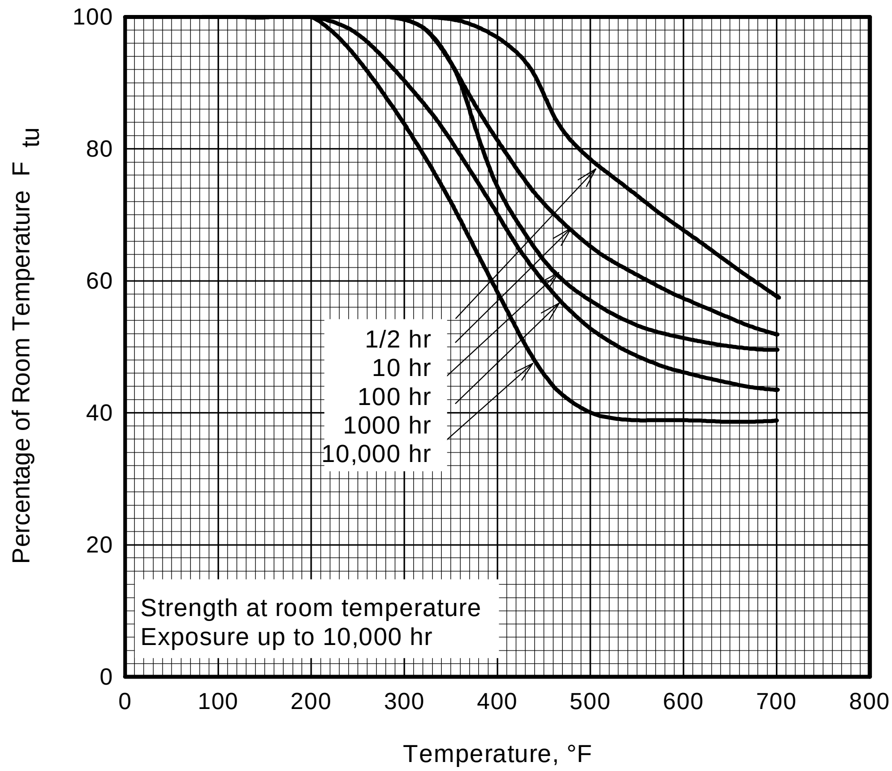

Figure 3.2.3.3.1(c). Effect of exposure at elevated temperatures on the room-temperature tensile ultimate strength (F_{tu}) of 2024-T62 aluminum alloy (all products).

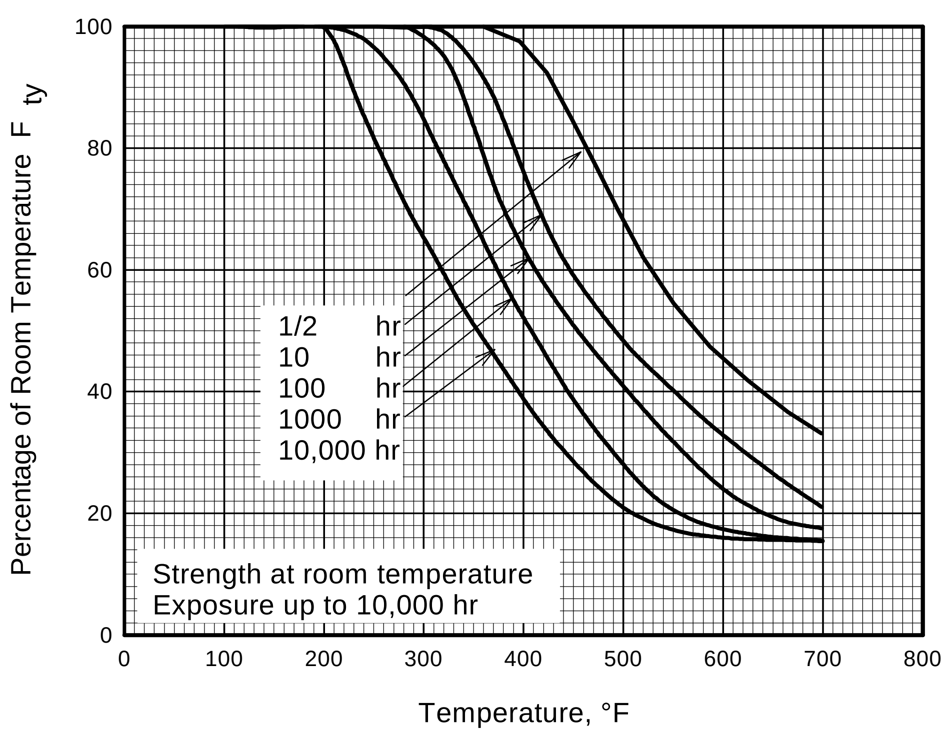

Figure 3.2.3.3.1(d). Effect of exposure at elevated temperatures on the room-temperature tensile yield strength (F_{ty}) of 2024-T62 aluminum alloy (all products).

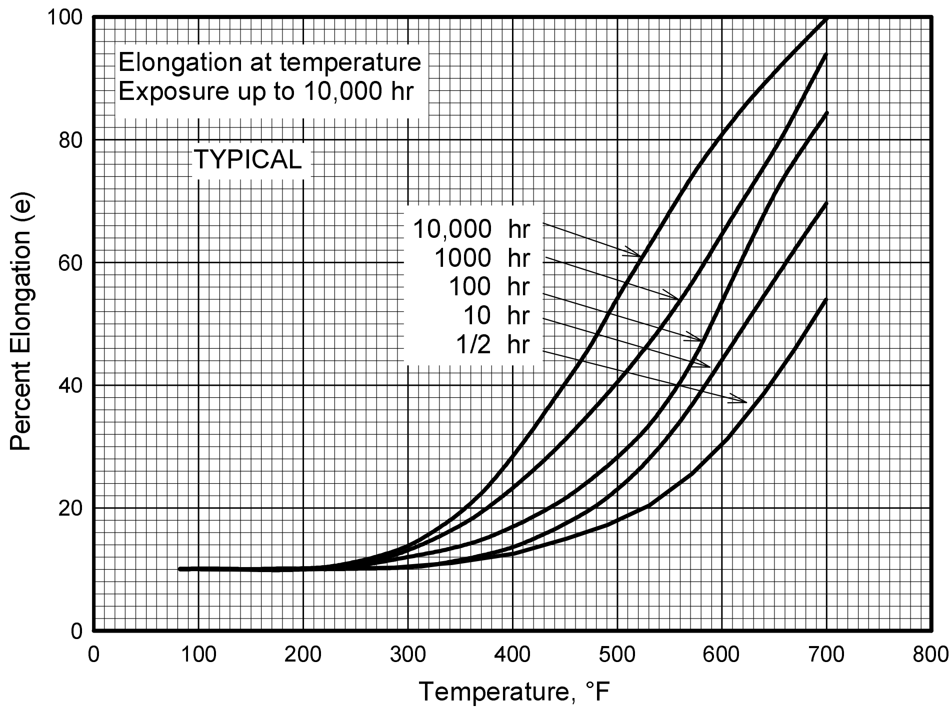

Figure 3.2.3.3.5(a). Effect of temperature on the elongation of 2024-T62 aluminum alloy (all products).

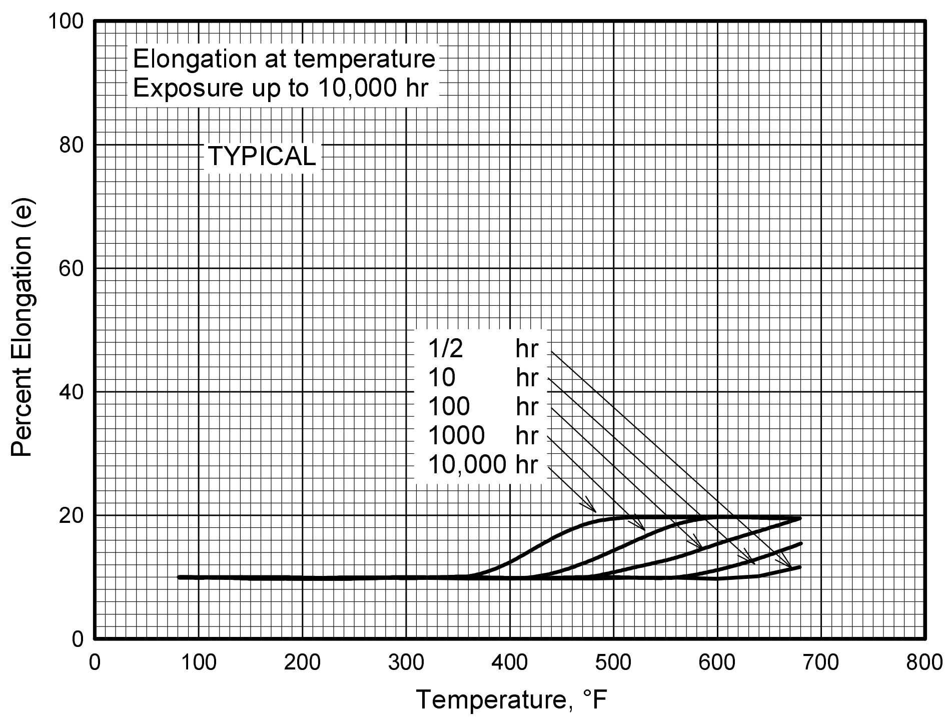

Figure 3.2.3.3.5(b). Effect of exposure at elevated temperatures on the elongation of 2024-T62 aluminum alloy (all products).

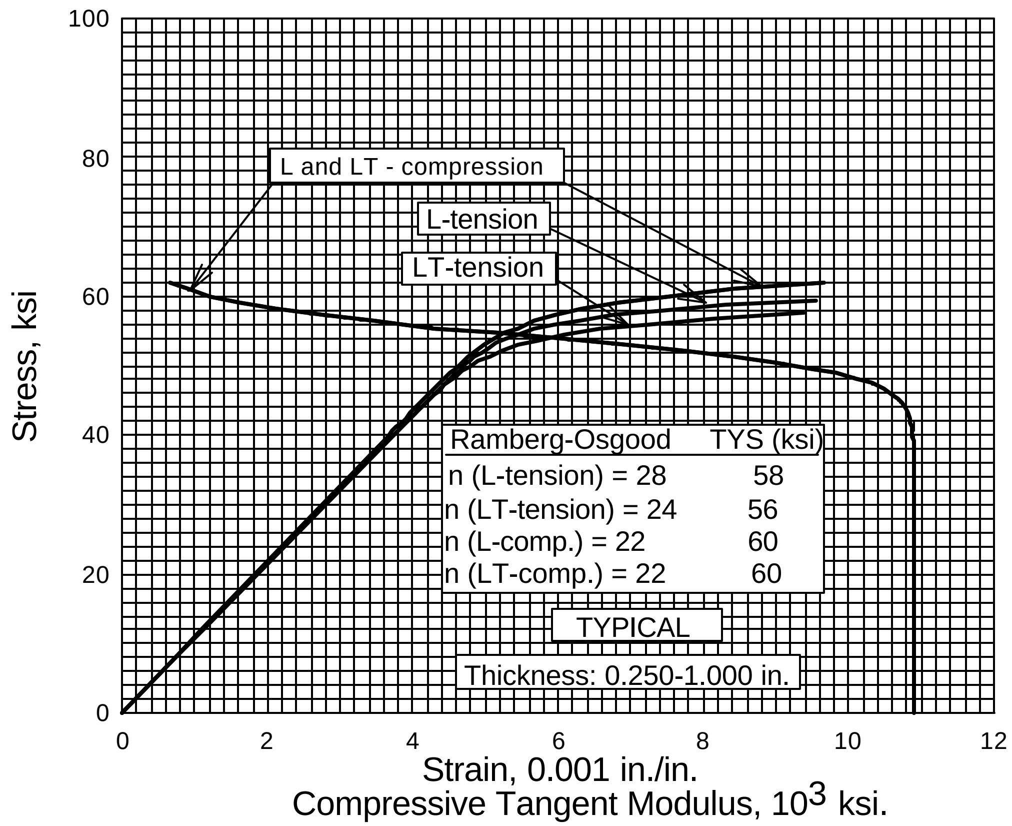

Figure 3.2.3.3.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2024-T62 aluminum alloy plate at room temperature.

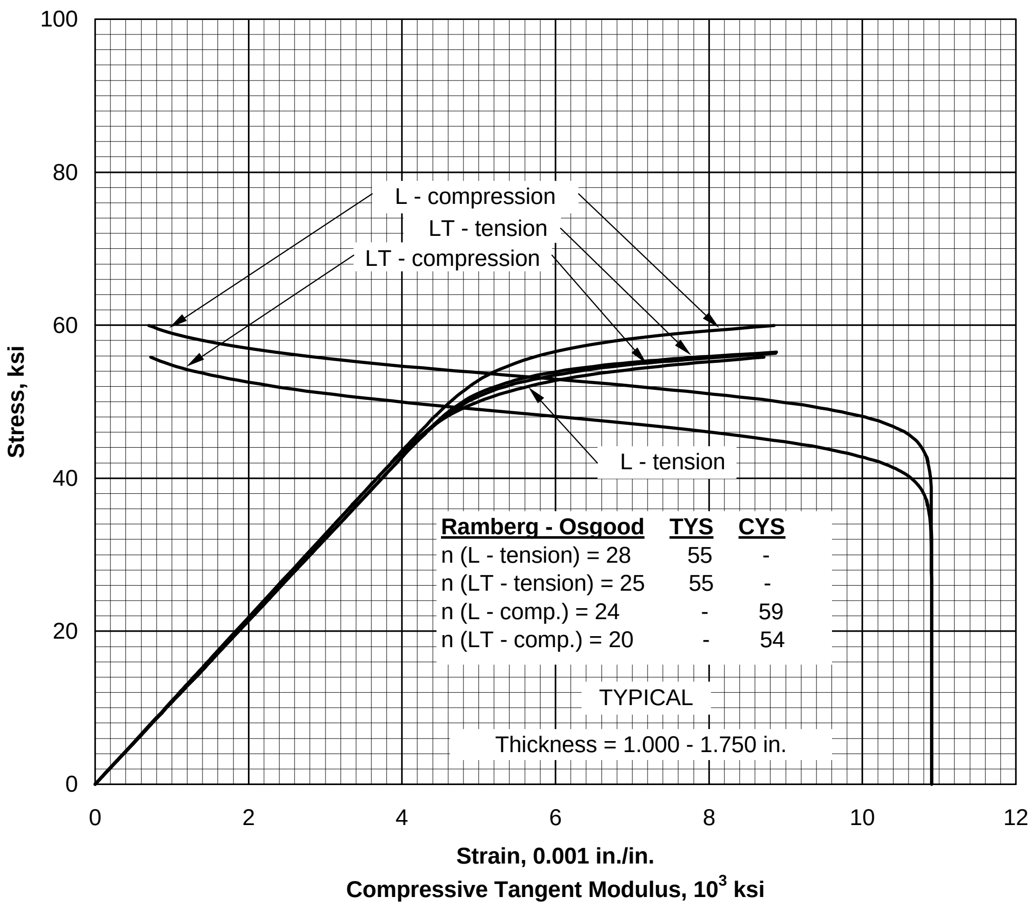

Figure 3.2.3.3.6(b) Typical tension and compression stress-strain and compression tangent modulus curves for 2024-T62 aluminum alloy plate at room temperature. Note, the data to generate these curves may have been from clad product, however, they are shown here without secondary modulus since it could not be positively confirmed the product was cladded.

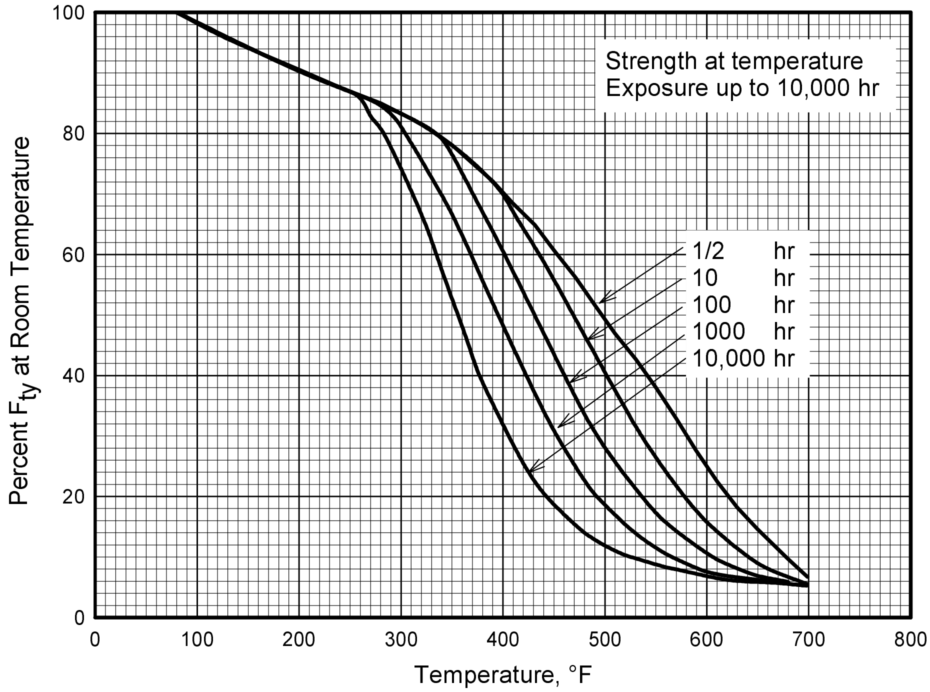

Figure 3.2.3.4.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

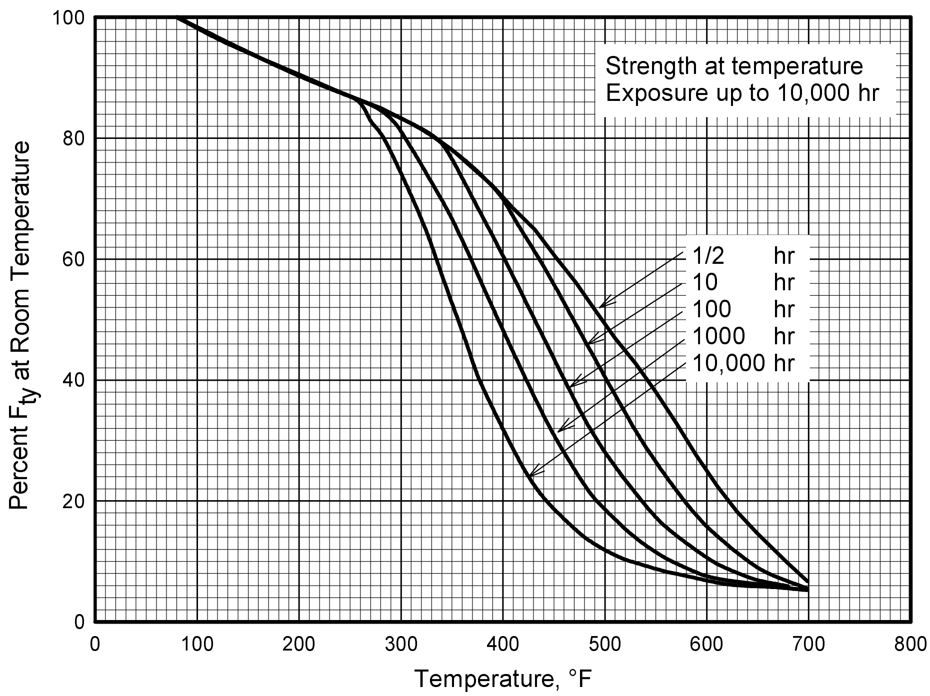

Figure 3.2.3.4.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

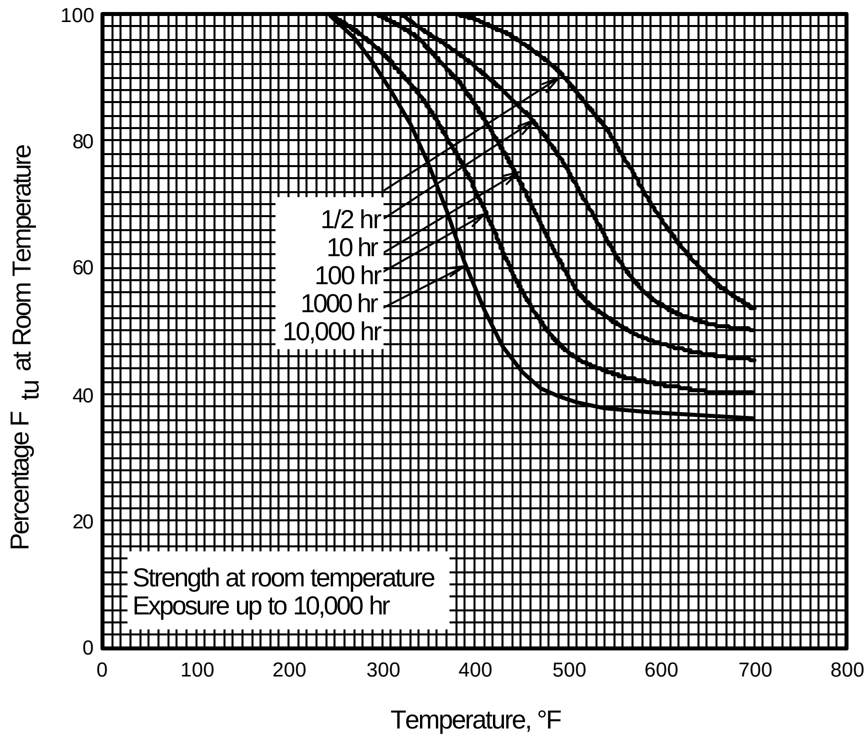

Figure 3.2.3.4.1(c). Effect of exposure at elevated temperatures on room-temperature tensile ultimate strength (F_{tu}) of 2024-T81 aluminum alloy sheet.

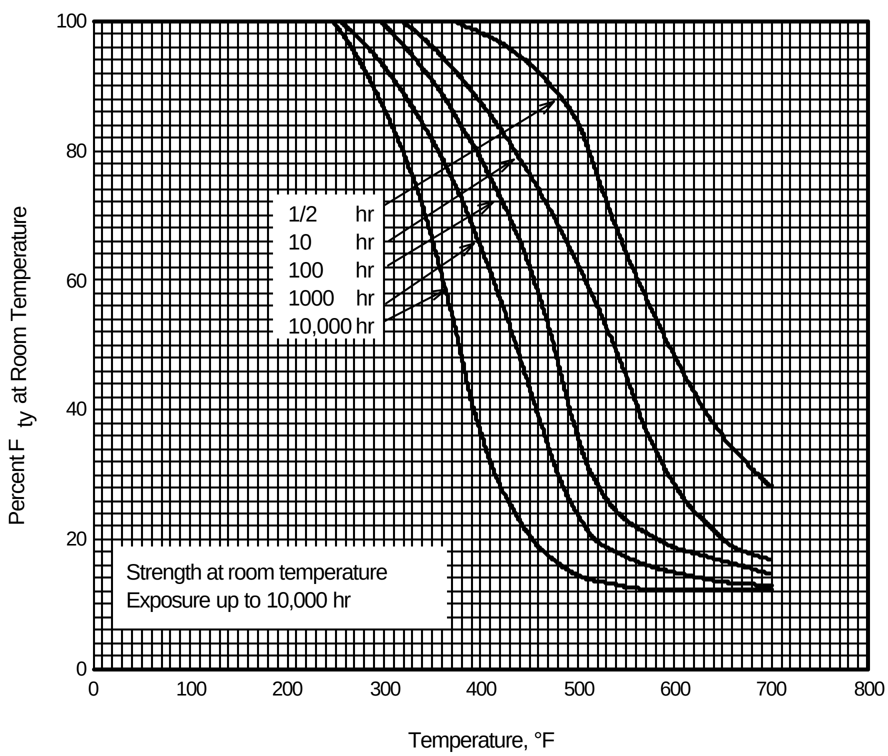

Figure 3.2.3.4.1(d). Effect of exposure at elevated temperatures on the room temperature tensile yield strength (F_{ty}) of 2024-T81 aluminum alloy sheet.

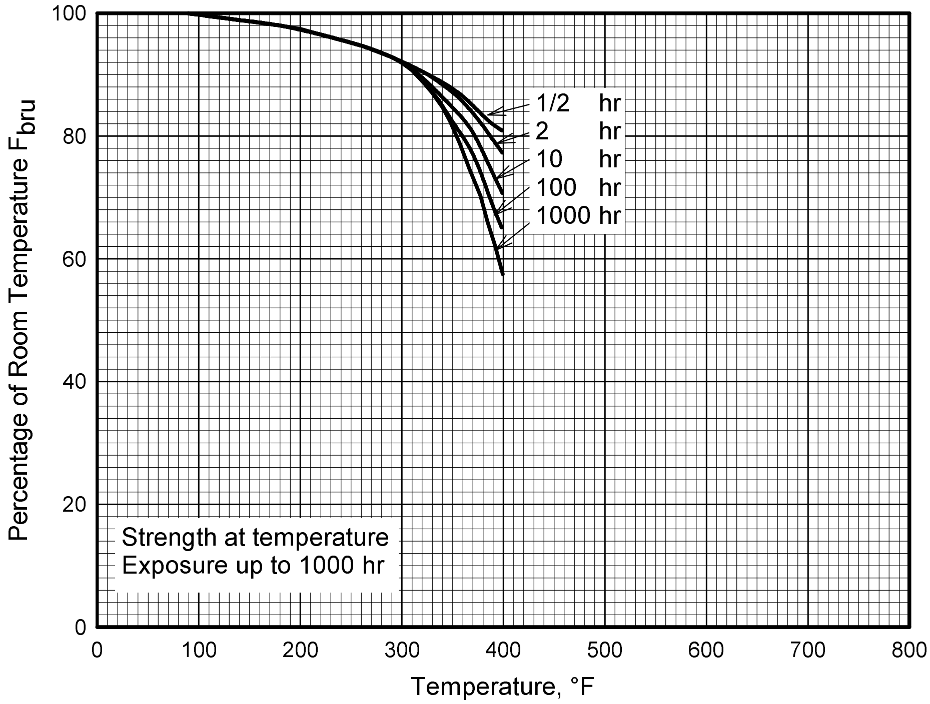

Figure 3.2.3.4.3(a). Effect of temperature on the bearing ultimate strength (F_{bru}) of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

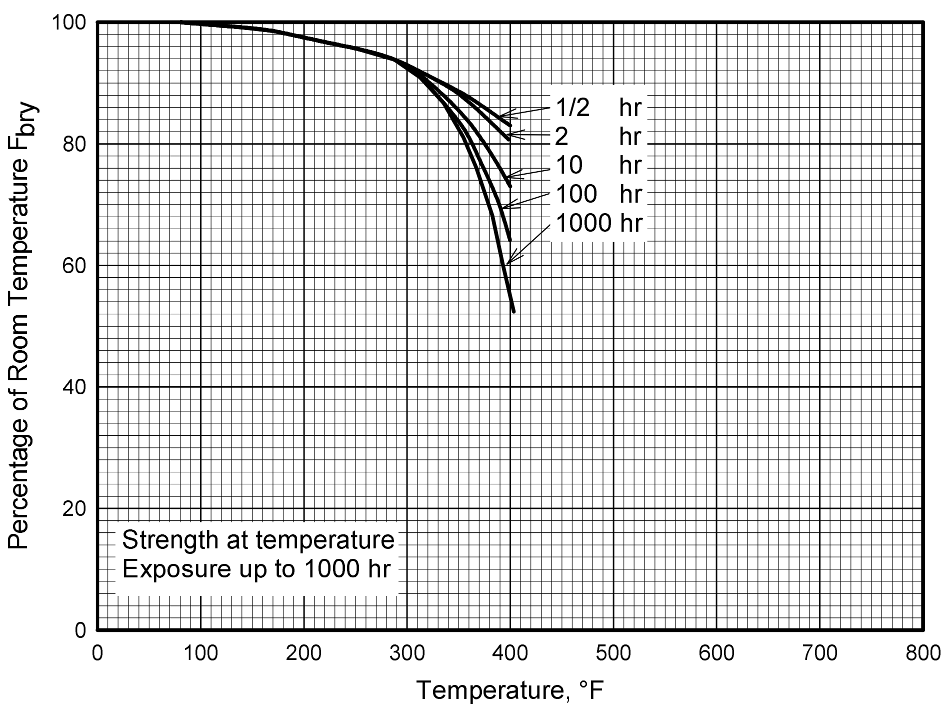

Figure 3.2.3.4.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

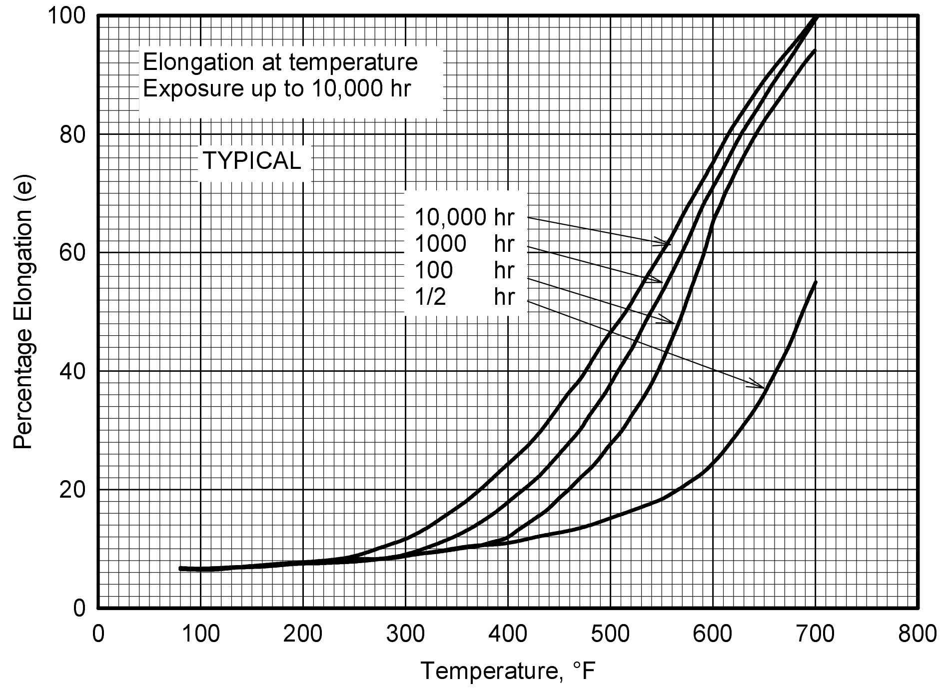

Figure 3.2.3.4.5(a). Effect of temperature on the elongation of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

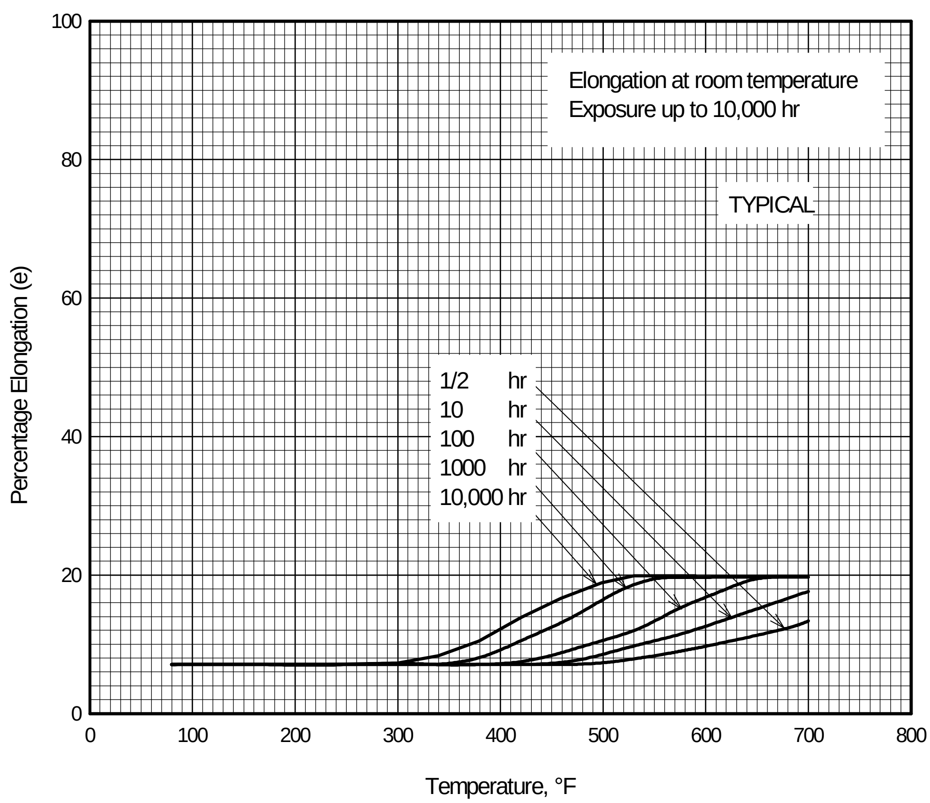

Figure 3.2.3.4.5(b). Effect of exposure at elevated temperatures on the room temperature elongation of 2024-T81, T851, T8510, and T8511 aluminum alloy (all products).

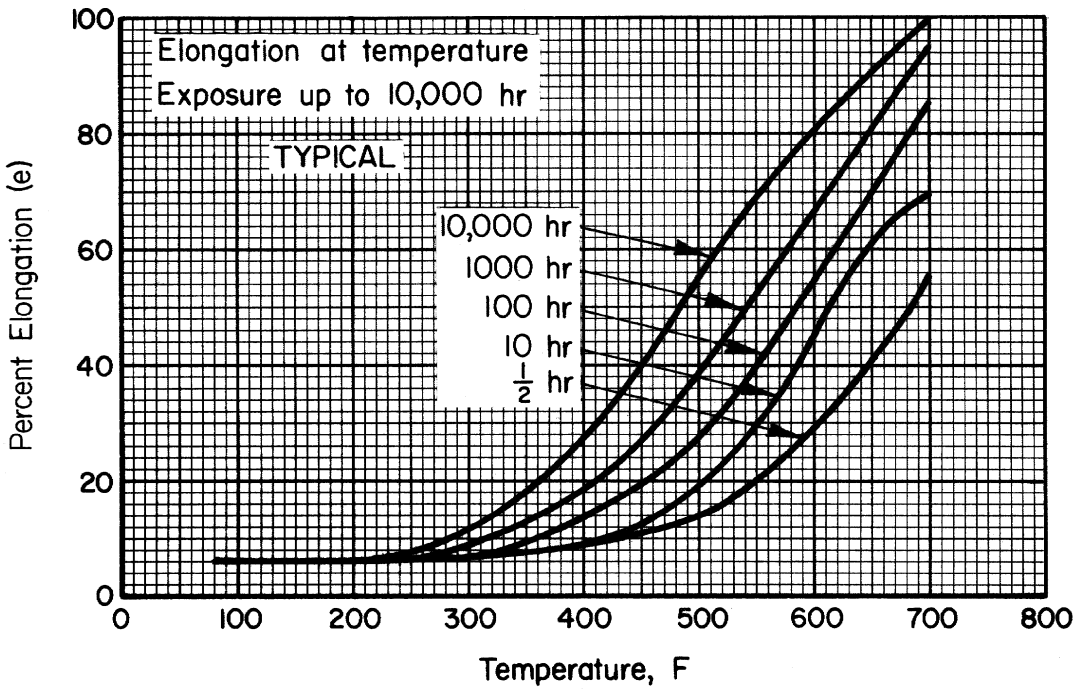

Figure 3.2.3.5.5(a). Effect of temperature on the elongation (e) of 2024-T861 (T86) aluminum alloy sheet.

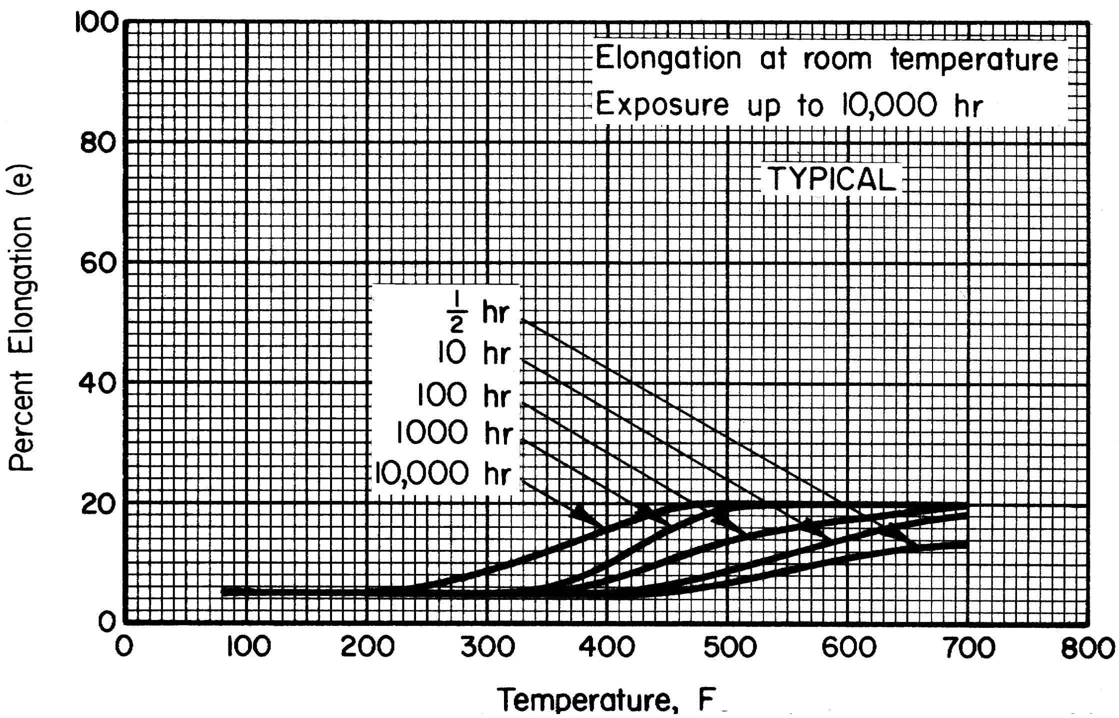

Figure 3.2.3.5.5(b). Effect of exposure at elevated temperatures on the room temperature elongation (e) of 2024-T861 (T86) aluminum alloy sheet.

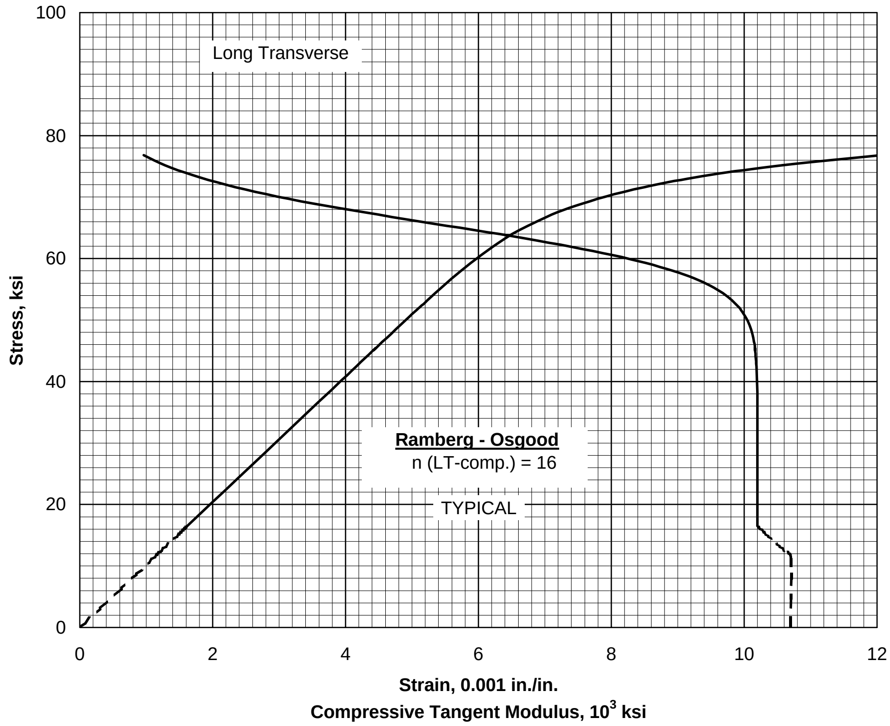

Figure 3.2.3.5.6(a). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T861 aluminum alloy sheet at room temperature.

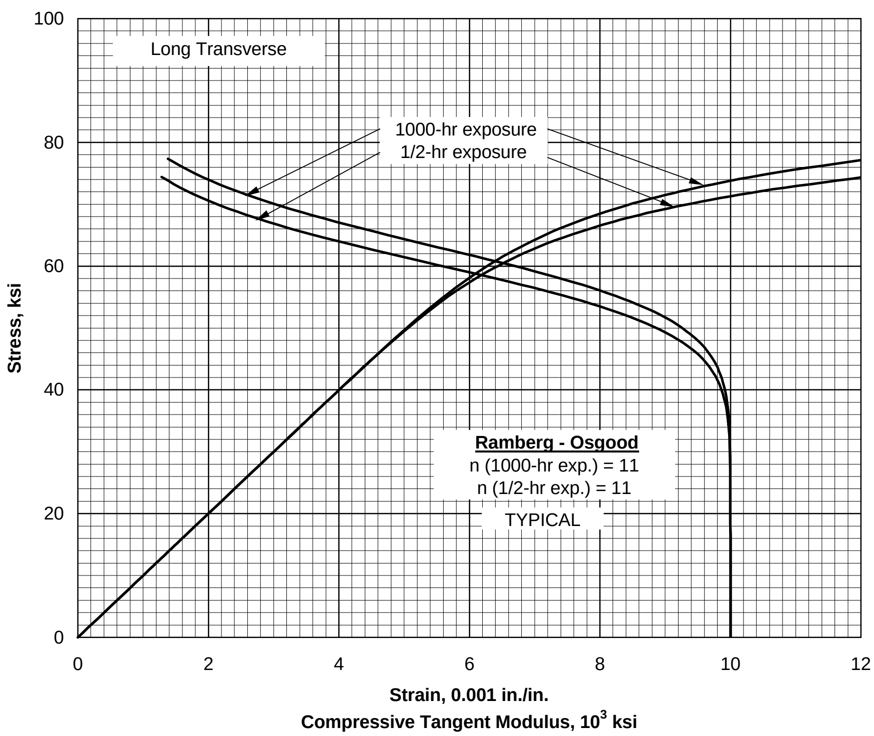

Figure 3.2.3.5.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for clad 2024-T861 aluminum alloy sheet at 200°F.

3.2.4 2025 ALLOY

3.2.4.0 *Comments and Properties* — 2025 is a heat-treatable Al-Cu forging alloy for which applications have been limited primarily to propellers. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.2.4 for comments regarding the weldability of the alloy.

A material specification for 2025 aluminum alloy is presented in Table 3.2.4.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.4.0(b). The effect of temperature on thermal expansion is shown in Figure 3.2.4.0.

Table 3.2.4.0(a). Material Specification for 2025 Aluminum Alloy

Specification	Form
AMS 4130	Die forging

Table 3.2.4.0(b). Design Mechanical and Physical Properties of 2025 Aluminum Alloy Die Forging

Specification	AMS 4130
Form	Die forging
Temper	T6
Thickness, in.	≤ 4.000
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	55
T[a]	52
F_{ty}, ksi:	
L	33
T[a]	32
F_{cy}, ksi:	
L	...
T[a]	...
F_{su}, ksi	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent:	
L	11
T[a]	8
E, 10^3 ksi	10.3
E_c, 10^3 ksi	10.5
G, 10^3 ksi	3.9
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.101
C, Btu/(lb)(°F)	0.23 (at 212°F)
K, Btu/[(hr)(ft^2)(°F)/ft]	90 (at 77°F)
α, 10^{-6} in./in./°F	See Figure 3.2.4.0

a T indicates any grain direction within ±15° of being perpendicular to the forging flow lines.

3.2.6 2124 ALLOY

3.2.6.0 *Comments and Properties* — 2124 is an Al-Cu alloy available in the form of plate in thicknesses of 1 through 6 inches. This alloy is a high purity version of alloy 2024. The higher purity in conjunction with special production processing provides higher elongation in the short-transverse direction and improved fracture toughness over that exhibited by conventionally produced 2024 alloy. The alloy is currently only produced in the T851 temper. The alloy like 2024 has excellent properties and creep resistance at elevated temperatures. The alloy in the T851 temper has good resistance to stress corrosion. Refer to Section 3.1.2.3.1 for information regarding resistance of the alloy to stress-corrosion cracking. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy. The physical properties are essentially the same as those for 2024-T851 plate.

Applicable material specification for 2124-T851 plate is presented in Table 3.2.6.0(a). Room-temperature mechanical properties are shown in Table 3.2.6.0(b).

Table 3.2.6.0(a). Material Specification for 2124 Aluminum Alloy

Specification	Form
AMS 4101	Plate
AMS-QQ-A-250/29	Plate

The temper index for 2124 is as follows:

Section	Temper
3.2.6.1	T851

3.2.6.1 *T851 Temper* — Elevated temperature data are presented in Figures 3.2.6.1.1(a) and (b). Typical tensile stress-strain, compressive stress-strain, and compressive tangent-modulus curves are presented in Figures 3.2.6.1.6(a) and (b). Fatigue crack-propagation data for plate are presented in Figures 3.2.6.1.9(a) through (e).

Table 3.2.6.0(b). Design Mechanical and Physical Properties of 2124 Aluminum Alloy Plate

Specification	AMS 4101 and AMS-QQ-A-250/29										
Form	Plate										
Temper	T851										
Thickness, in.	1.000-1.500	1.501-2.000		2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000	
Basis	S	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:											
F_{tu}, ksi:											
L	66	66	68	65	68	65	67	64	66	63	65
LT	66	66	68	65	68	65	67	64	66	63	65
ST	64[a]	64	66	63	64	62	63	61	62	58	59
F_{ty}, ksi:											
L	57	57	61	57	61	56	60	55	58	54	56
LT	57	57	61	57	61	56	60	55	58	54	56
ST	55[a]	55	59	55	59	54	57	53	55	51	53
F_{cy}, ksi:											
L	57	57	61	56	60	55	59	53	56	52	54
LT	57	57	61	57	61	56	60	55	58	54	56
ST	...	57	61	58	62	57	61	57	60	56	58
F_{su}, ksi:											
L	...	38	39	38	39	38	39	37	38	37	38
LT	...	38	39	38	39	38	39	37	38	37	38
ST	...	36	37	36	37	36	37	35	36	35	36
F_{bru}[b], ksi:											
(e/D = 1.5)	...	97	100	96	100	96	99	94	97	93	96
(e/D = 2.0)	...	126	130	125	130	125	128	123	126	121	125
F_{bry}[b], ksi:											
(e/D = 1.5)	...	79	84	80	85	80	85	79	84	79	82
(e/D = 2.0)	...	91	98	92	99	92	99	92	97	91	95
e, percent (S-basis):											
L	6	6	...	6	...	5	...	5	...	5	...
LT	5	5	...	4	...	4	...	4	...	4	...
ST	1.5[a]	1.5	...	1.5	...	1.5	...	1.5	...	1.5	...
E, 10^3 ksi	10.4										
E_c, 10^3 ksi	10.9										
G, 10^3 ksi	4.0										
μ	0.33										
Physical Properties:											
ω, lb/in.^{3}	0.100										
C, Btu/(lb)(°F)	0.21 (at 212°F)										
K, Btu/[(hr)(ft^2)(°F)/ft]	87 (at 77°F)										
α, 10^{-6} in./in./°F	12.6 (68°F to 212°F)										

a Applicable to 1.500-inch thickness only.
b Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

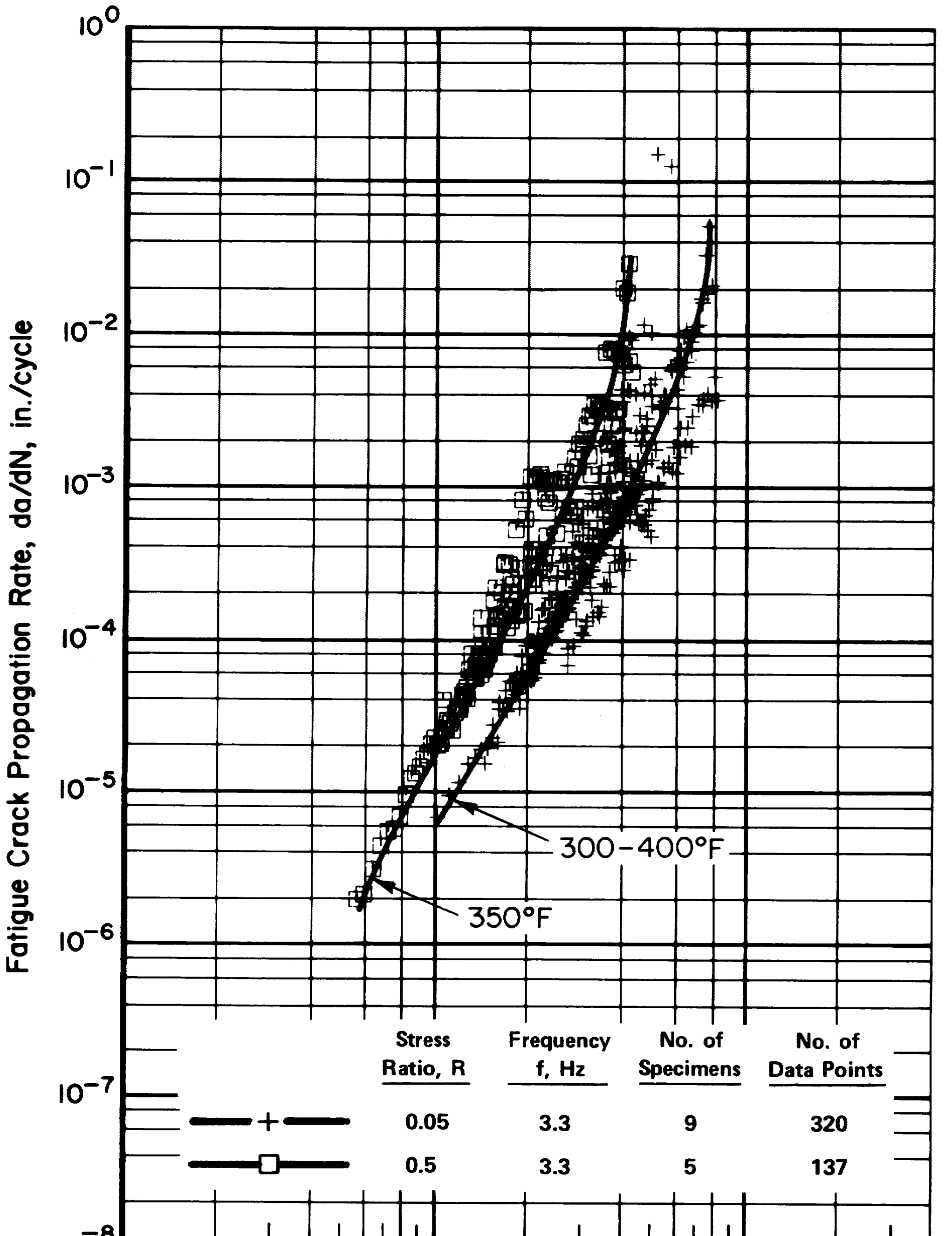

Figure 3.2.6.1.9(e). Fatigue-crack-propagation data for 2.0-inch thick, 2124-T851 aluminum alloy plate. [Reference 3.2.6.1.9(a)].

Specimen Thickness:	*0.25-0.45 inch*	*Environment:*	*Lab air*
Width:	*11.75 inches*	*Temperature:*	*300-400 °F*
Type:	*M(T)*	*Orientation:*	*T-L*

3.2.7 2219 ALLOY

3.2.7.0 *Comments and Properties* — 2219 is an Al-Cu alloy available in a wide variety of product forms. As shown in Table 3.1.2.3.1(a), 2219-T351X and -T37 rolled plate and extruded shapes have a 'D' SCC rating. This is the lowest rating and means that SCC failures have occurred in service or would be anticipated if there is any sustained stress. In-service failures are caused by stressed produced by any combination of sources including solution heat treatment, straightening, forming, fit-up, clamping, sustained service loads or high service compression stresses that produce residual tensile stresses. These stresses may be tension or compression as well as the stresses due to the Poisson effect, because the actual failures are caused by the resulting sustained shear stresses. Pin-hole flaws in corrosion protection are sufficient for SCC. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy. It has been used in critical cryogenic applications as well as those applications in which high strength and creep resistance at relatively high temperatures (400 to 600°F) are required.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 2219 are presented in Table 3.2.7.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.2.7.0(b_1) through (d). The effect of temperature on the physical properties is shown in Figure 3.2.7.0.

Table 3.2.7.0(a). Material Specifications for 2219 Aluminum Alloy

Specification	Form
AMS 4031	Sheet and plate
AMS-QQ-A-250/30	Sheet and plate
AMS 4162	Extrusion
AMS 4163	Extrusion
AMS 4144	Hand forging

The temper index for 2219 is as follows:

Section	Temper
3.2.7.1	T62
3.2.7.2	T81, T851, T8510, and T8511
3.2.7.3	T852
3.2.7.4	T87

3.2.7.1 *T62 Temper* — Elevated temperature data for this temper are presented in Figures 3.2.7.1.1(a) and (b). Typical room-temperature tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy sheet and plate for this temper are shown in Figures 3.2.7.1.6(a) and (b).

3.2.7.2 *T81 and T851X Tempers* — Elevated temperature data for these tempers are presented in Figures 3.2.7.2.1(a) and (b). Typical room-temperature tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy for this condition are shown in Figures 3.2.7.2.6(a) and (b). Notched fatigue data for plate are presented in Figures 3.2.7.2.8(a) through (d).

3.2.7.3 *T852 Temper* — Typical room-temperature tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy for this temper are shown in Figures 3.2.7.3.6(a) through (e).

3.2.7.4 *T87 Temper* — Elevated temperature data for this temper are presented in Figures 3.2.7.4.1(a) and (b). Typical room-temperature tensile and compressive stress-strain, compressive tangent-modulus, and full-range tensile stress-strain curves for 2219 aluminum alloy sheet and plate for this temper are shown in Figures 3.2.7.4.6(a) through (e).

Table 3.2.7.0(b_1). Design Mechanical and Physical Properties of 2219 Aluminum Alloy Sheet and Plate

Specification	AMS 4031 & AMS-QQ-A-250/30		AMS-QQ-A-250/30													
Form	Sheet and plate															
Temper	T62[a]		T81		T851											
Thickness, in.	0.020-2.000		0.020-0.249		0.250-1.000		1.001-2.000		2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																
F_{tu}, ksi:																
L	54	55	61	62	61	62	61	62	...	...	...	...	...	...	...	...
LT	54	55	62	63	62	63	62	63	62	63	60	61	59	60	57	58
F_{ty}, ksi:																
L	36	37	47	48	47	48	47	48	...	...	...	...	...	...	...	...
LT	36	37	46	47	46	47	46	47	45	46	44	45	43	44	42	43
F_{cy}, ksi:																
L	37	39	47	48	47	48	47	48	...	...	...	...	...	...	...	...
LT	37	38	48	49	48	49	48	49	...	...	...	...	...	...	...	...
F_{su}, ksi	31	32	35	35	36	36	36	36	...	...	...	...	...	...	...	...
F_{bru}[b], ksi:																
(e/D = 1.5)	84	85	95	96	95	96	95	96	...	...	...	...	...	...	...	...
(e/D = 2.0)	107	109	121	123	121	123	121	123	...	...	...	...	...	...	...	...
F_{bry}[b], ksi:																
(e/D = 1.5)	62	64	76	78	76	78	76	78	...	...	...	...	...	...	...	...
(e/D = 2.0)	79	81	92	94	94	94	92	94	...	...	...	...	...	...	...	...
e, percent (S-basis):																
LT	[c]	...	[c]	...	8	...	7	...	6	...	5	...	5	...	4	...
E, 10^3 ksi	10.5															
E_c, 10^3 ksi	10.8															
G, 10^3 ksi	4.0															
μ	0.33															
Physical Properties:																
ω, lb/in.^{3}	0.103															
C, K, and α	See Figure 3.2.7.0															

a Design allowables were based upon data obtained from testing samples of material, supplied in O and F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

b Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

c T62 and T81: 0.020-0.039 in., 6 percent, 0.040-0.249 in., 7 percent; T62: 0.250-1.000 in., 8 percent, 1.001-2.000 in., 7 percent.

Table 3.2.7.0(c). Design Mechanical and Physical Properties of 2219 Aluminum Alloy Hand Forging

Specification	AMS 4144							
Form	Hand Forging							
Temper	T852							
Thickness, in.	<2.000	2.000-4.000	4.001-6.000	6.001-8.000	8.001-10.000	10.001-12.000	12.001-14.000	14.001-17.000
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	62	62	58	57	56	54	53	51
LT	62	62	56	55	54	53	52	50
ST	...	60	56	55	54	53	52	50
F_{ty}, ksi:								
L	50	50	44	43	42	41	40	39
LT	49	49	42	41	41	40	40	39
ST	...	46	41	40	39	39	38	37
F_{cy}, ksi:								
L	...	46	40	39	...	...	...	...
LT	...	47	40	39	...	...	...	...
ST	...	47	41	40	...	...	...	...
F_{su}, ksi:								
L	...	37	35	35	...	...	...	...
LT	...	36	34	35	...	...	...	...
ST	...	32	32	33	...	...	...	...
F_{bru}[a], ksi:								
(e/D = 1.5)	...	...	...	80	...	...	...	...
(e/D = 2.0)	...	104	100	102	...	...	...	...
F_{bry}[a], ksi:								
(e/D = 1.5)	...	76	65	64	...	...	...	...
(e/D = 2.0)	...	89	76	75	...	...	...	...
e, percent:								
L	6	6	6	6	6	6	6	6
LT	4	4	4	4	3	3	3	3
ST	...	3	3	3	3	2	2	2
E, 10^3 ksi	10.2							
E_c, 10^3 ksi	10.4							
G, 10^3 ksi	3.9							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.103							
C, K, and α	See Figure 3.2.7.0							

a Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.2.7.0(d). Design Mechanical and Physical Properties of 2219 Aluminum Alloy Extruded Shapes

Specification	AMS 4162 and AMS 4163[a]	
Form	Extruded shapes	
Temper	T8511	
Cross-Sectional Area, in.^{2}	$\leq$25	
Thickness or Diameter,[b] in.	$\leq$0.499	0.500-2.999
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	58	58
LT[c]	56	56
F_{ty}, ksi:		
L	42	42
LT[c]	39	39
F_{cy}, ksi:		
L	43	42
LT	43	41
F_{su}, ksi	33	33
F_{bru}[d], ksi:		
(e/D = 1.5)	87	81
(e/D = 2.0)	113	107
F_{bry}[d], ksi:		
(e/D = 1.5)	69	67
(e/D = 2.0)	84	82
e, percent:		
L	6	6
LT[c]	4	4
E, 10^3 ksi	10.5	
E_c, 10^3 ksi	10.8	
G, 10^3 ksi	4.0	
μ	0.33	
Physical Properties:		
ω, lb/in.^{3}	0.103	
C, K, and α	See Figure 3.2.7.0	

a Design allowables for extrusions procured to AMS 4163 were based upon data obtained from testing samples of material, supplied in T3511 temper, which were precipitation heat treated by suppliers to demonstrate response to aging treatment.
b The mechanical properties are to be based upon the thickness at the time of quench.
c Applicable providing LT dimension is $\geq$2.500 inches.
d Bearing values are "dry pin" values per Section 1.4.7.1.

3.2.8 2424 ALLOY

3.2.8.0 ***Comments and Properties*** — 2424 is a heat-treatable Al-Cu alloy which provides better ductility than 2024. 2424 is available in the form of bare and clad sheet.

Material specifications for 2424 are presented in Table 3.2.8.0(a). Room-temperature mechanical properties are presented in Tables 3.2.8.0(b_1) and 3.2.8.0(b_2).

Table 3.2.8.0(a). Material Specifications for 2424 Aluminum Alloy

Specification	Form
AMS 4270 (Clad)	Sheet
AMS 4273 (Bare)	Sheet

The temper index for 2424 is as follows:

Section	Temper
3.2.8.1	T3

Table 3.2.8.0(b_1). Design Mechanical and Physical Properties of Bare 2424-T3 Aluminum Alloy Sheet

Specification	AMS 4273	
Form	Sheet	
Temper	T3	
Thickness, in.	0.020 - 0.128	
Basis	A	B
Mechanical Properties:		
F_{tu}, ksi:		
L	65	66
LT	63	65
F_{ty}, ksi:		
L	49	51
LT	42[c]	45
F_{cy}, ksi:		
L	42	45
LT	46	49
F_{su},[a] ksi	41	43
F_{bru},[b] ksi:		
(e/D = 1.5)	97	100
(e/D = 2.0)	129	133
F_{bry},[b] ksi:		
(e/D = 1.5)	62	66
(e/D = 2.0)	78	83
e, percent (S-basis):		
L	...	...
LT	15	...
E, 10^3 ksi		
L	9.8	
LT	10.3	
E_c, 10^3 ksi		
L	10.0	
LT	10.5	
G, 10^3 ksi	...	
μ	0.34	
Physical Properties:		
ω, lb/in.^{3}	0.100	
C, Btu/(lb)(°F)	...	
K, Btu/[(hr)(ft^2)(°F)/ft]	...	
α, 10^{-6} in./in./°F	...	

a Determined in accordance with ASTM B769.
b Bearing values are "dry pin" values per Section 1.4.7.1.
c S-basis. The T_{99} value is 43.71 ksi.

Table 3.2.8.0(b_2). Design Mechanical and Physical Properties of Clad 2424-T3 Aluminum Alloy Sheet

Specification	AMS 4270	
Form	Sheet	
Temper	T3	
Thickness, in.	0.063 - 0.128	
Basis	A	B
Mechanical Properties:		
F_{tu}, ksi:		
L	64	65
LT	61	64
F_{ty}, ksi:		
L	46	49
LT	40[c]	44
F_{cy}, ksi:		
L	40	44
LT	43	47
F_{su},[a] ksi	41	43
F_{bru},[b] ksi:		
(e/D = 1.5)	94	98
(e/D = 2.0)	121	126
F_{bry},[b] ksi:		
(e/D = 1.5)	60	66
(e/D = 2.0)	70	77
e, percent (S-basis):		
L	...	...
LT	15	...
E, 10^3 ksi		
L	9.8	
LT	10.3	
E_c, 10^3 ksi		
L	10	
LT	10.5	
G, 10^3 ksi	...	
μ	0.34	
Physical Properties:		
ω, lb/in.^{3}	0.100	
C, Btu/(lb)(°F)	...	
K, Btu/[(hr)(ft^2)(°F)/ft]	...	
α, 10^{-6} in./in./°F	...	

a Determined in accordance with ASTM B769.
b Bearing values are "dry pin" values per Section 1.4.7.1.
c S-basis. The T_{99} value is 42.79 ksi.

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3.2.9 2519 ALLOY

3.2.9.0 ***Comments and Properties*** — 2519 is an Al-Cu weldable alloy available in plate. This armor plate has equivalent ballistic protection characteristics compared to 7039 and superior stress-corrosion cracking resistance compared to 5083. See Section 3.1.2.3 for comments regarding resistance of the alloy to stress-corrosion cracking. The general corrosion characteristics of 2519 are similar to 2219. 2519 in the T87 temper has approximately 20 percent higher yield strength than 2219-T87 plate. 2519-T87 is easily welded with filler alloy 2319. Yield strengths of welded butt joints are higher than other commercially available alloys. 2519 can be post weld aged or post weld heat treated and aged to obtain improved mechanical properties compared to "as welded" condition. See Section 3.1.3.4 for further information regarding the weldability of the alloy.

A material specification of 2519 is presented in Table 3.2.9.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.9.0(b).

Table 3.2.9.0(a). Material Specification for 2519 Aluminum Alloy

Specification	Form
MIL-A-46192	Plate

The temper index for 2519 is as follows:

Section	Temper
3.2.9.1	T87

3.2.9.1 ***T87 Temper*** — Typical room-temperature tensile and compressive stress-strain and compressive tangent-modulus curves are presented in Figures 3.2.9.1.6(a) and (b).

Table 3.2.9.0(b). Design Mechanical and Physical Properties of 2519 Aluminum Alloy Plate

Specification	MIL-A-46192			
Form	Plate			
Temper	T87			
Thickness or Diameter, in.	0.250-1.000	1.001-2.000	2.001-3.000	3.001-4.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	66	66	67	68
LT	68	68	68	68
ST	...	...	63	62
F_{ty}, ksi:				
L	59	59	60	61
LT	58	58	59	59
ST	...	...	55	55
F_{cy}, ksi:				
L	57	57	58	58
LT	60	60	61	61
ST	...	...	58	58
F_{su}, ksi	42	41	41	40
F_{bru}[a], ksi:				
(e/D = 1.5)	105	105	104	103
(e/D = 2.0)	135	134	133	131
F_{bry}[a], ksi:				
(e/D = 1.5)	85	85	87	87
(e/D = 2.0)	99	99	100	100
e, percent:				
L	10	9	8	7
LT	7	7	6	5
E, 10^3 ksi	10.5			
E_c, 10^3 ksi	10.8			
G, 10^3 ksi	4.0			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.102			
C, K, and α	...			

a See Table 3.1.2.1.1. Bearing values are "dry pin" per Section 1.4.7.1.

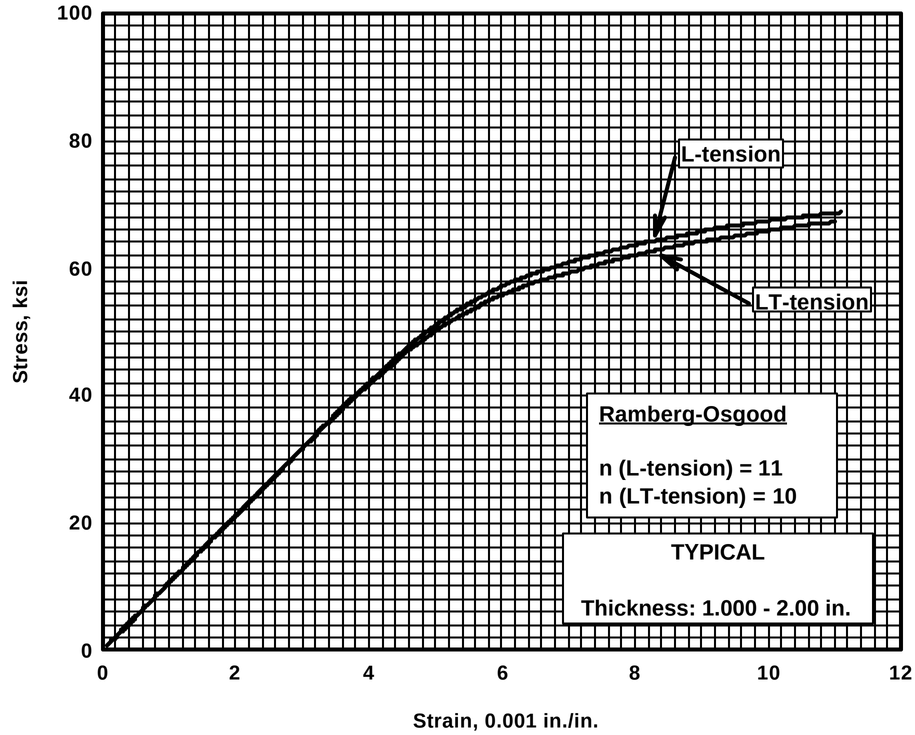

Figure 3.2.9.1.6(a). Typical tensile stress-strain curves for 2519-T87 aluminum alloy plate at room temperature.

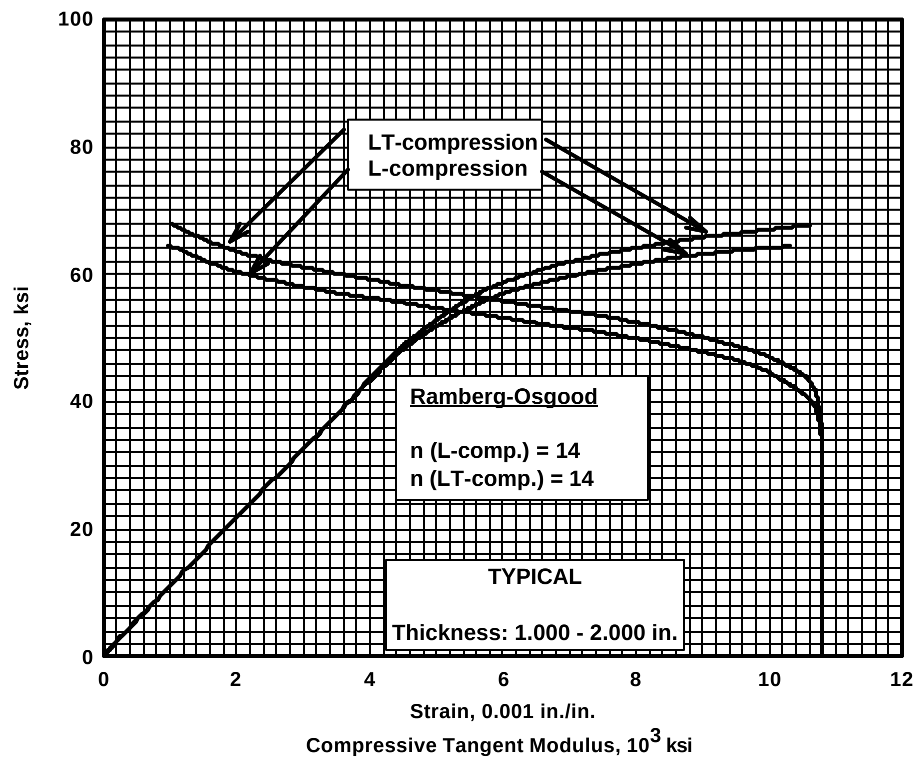

Figure 3.2.9.1.6(b). Typical compressive stress-strain and tangent-modulus curves for 2519-T87 plate at room temperature.

3.2.10 2524 ALLOY

3.2.10.0 ***Comments and Properties*** — 2524 is a heat-treatable Al-Cu alloy offering high toughness and improved resistance to fatigue crack growth relative to other available 2XXX sheet and plate materials. Sheet and plate is available in the T3 temper. Fatigue crack growth improvements are guaranteed through the material specification for Alclad 2524-T3 sheet and plate products. The static mechanical properties and general corrosion performance of Alclad 2524-T3 are similar to those of Alclad 2024-T3. This product has typically been used for formed structural aircraft parts requiring improved resistance to fatigue crack growth and high toughness with strength similar to Alclad 2024-T3, but usage is not limited to such applications.

A material specification for Alclad 2524-T3 sheet and plate is presented in Table 3.2.10.0(a). Room-temperature mechanical properties are shown in Table 3.2.10.0(b).

Table 3.2.10.0(a). Material Specifications for Alclad 2524-T3

Specification	Form
AMS 4296	Clad sheet and plate

The temper index for 2524 is as follows:

Section	Temper
3.2.10.1	T3

Table 3.2.10.0(b). Design Mechanical and Physical Properties of Alclad 2524-T3 Aluminum Alloy Sheet and Plate

Specification	AMS 4296						
Form	Sheet and Plate						
Condition	T3						
Thickness, in.	0.032-0.062	0.063-0.128		0.129-0.249		0.250-0.310	
Basis	S	A	B	A	B	A	B
Mechanical Properties:							
F_{tu}, ksi:							
L	59	61	62	62	62	62	63
LT	59	61[a]	62	62	62	62	63
F_{ty}, ksi:							
L	44	45	47	45	46	45	46
LT	39	40[b]	42	40	41	40	41
F_{cy}, ksi:							
L	38	39	41	39	40	39	40
LT	42	43	45	43	44	43	44
F_{su},[c] ksi:	40	41	42	42	42	42	43
F_{bru},[d] ksi:							
(e/D = 1.5)	93	97	98	98	98	98	100
(e/D = 2.0)	117	121	123	123	123	123	125
F_{bry},[d] ksi:							
(e/D = 1.5)	65	67	70	67	69	67	69
(e/D = 2.0)	76	78	82	78	80	78	80
e, percent (S-basis):							
LT	15	15	...	15	...	15	...
E, 10^3 ksi:							
Primary	10.3						
Secondary	9.8						
E_c, 10^3 ksi:							
Primary	10.5						
Secondary	10.0						
G, 10^3 ksi	...						
μ	0.35						
Physical Properties:							
ω, lb/in.^{3}	0.100						
C, K, and α	not available						

a S-basis value. The T_{99} value is 61.80 ksi.
b S-basis value. The T_{99} value is 41.20 ksi.
c Determined in accordance with ASTM B 831-93.
d Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

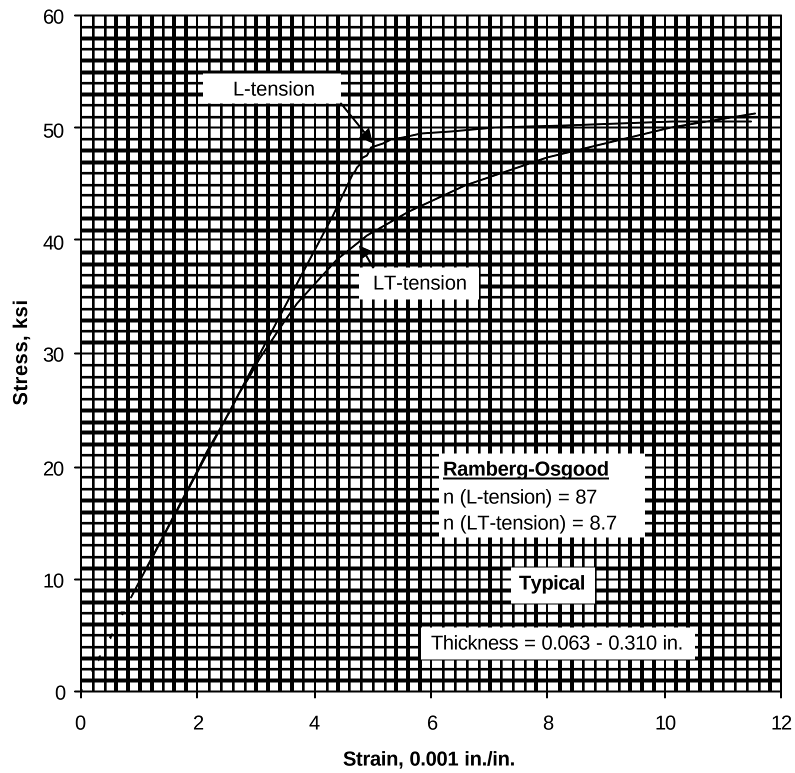

Figure 3.2.10.1.6(a). Typical tensile stress-strain curves for 2524-T3 clad aluminum alloy sheet and plate at room temperature.

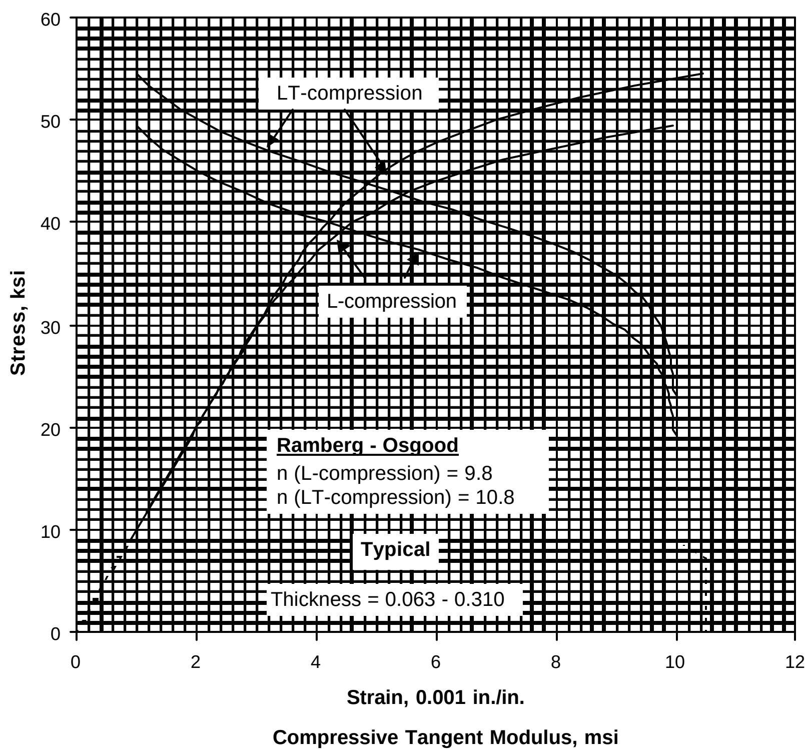

Figure 3.2.10.1.6(b). Typical compressive stress-strain and tangent modulus curves for 2524-T3 clad aluminum alloy sheet and plate at room temperature.

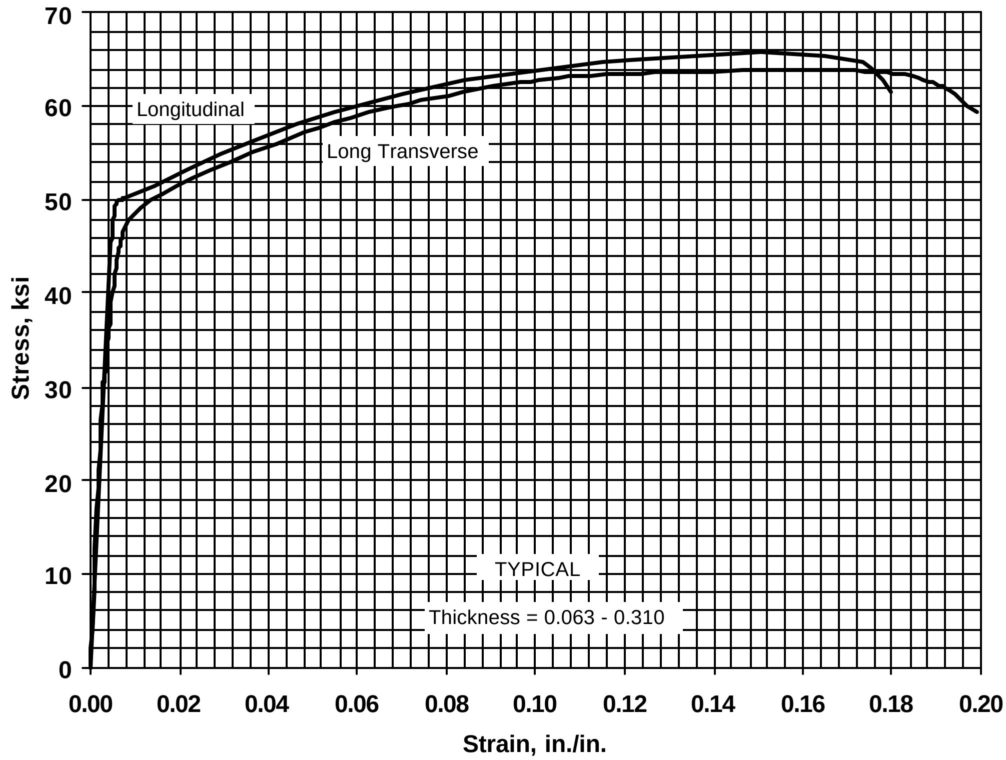

Figure 3.2.10.1.6(c). Typical tensile stress-strain curves (full range) for 2524-T3 clad aluminum alloy sheet and plate at room temperature.

3.2.11 2618 ALLOY

3.2.11.0 *Comments and Properties* — 2618 is an Al-Cu alloy which is available as hand and die forgings. It has excellent properties over a range of temperatures from -452 to 600°F and is usually used in applications where high strength and creep resistance are important considerations. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy. Refer to Section 3.1.2.3.1 for information regarding resistance of the alloy to stress-corrosion cracking.

Material specifications for 2618 aluminum alloy are presented in Table 3.2.11.0(a). Room-temperature mechanical and physical properties are shown in Table 3.2.11.0(b) and (c). The effect of temperature on the thermal expansion is shown in Figure 3.2.11.0.

Table 3.2.11.0(a). Material Specifications for 2618 Aluminum Alloy

Specification	Form
AMS 4132	Die and hand forgings
AMS-QQ-A-367	Forgings
AMS-A-22771	Die forging

The temper index for 2618 is as follows:

Section	Temper
3.2.11.1	T61

3.2.11.1 *T61 Temper* — Figures 3.2.11.1.1(a) through 3.2.11.1.5 present effect-of-temperature curves for various mechanical properties. Figure 3.2.11.1.6(a) presents tensile and compressive stress-strain and tangent-modulus curves at room temperature. Figure 3.2.11.1.6(b) is a full-range, tensile stress-strain curve at room temperature.

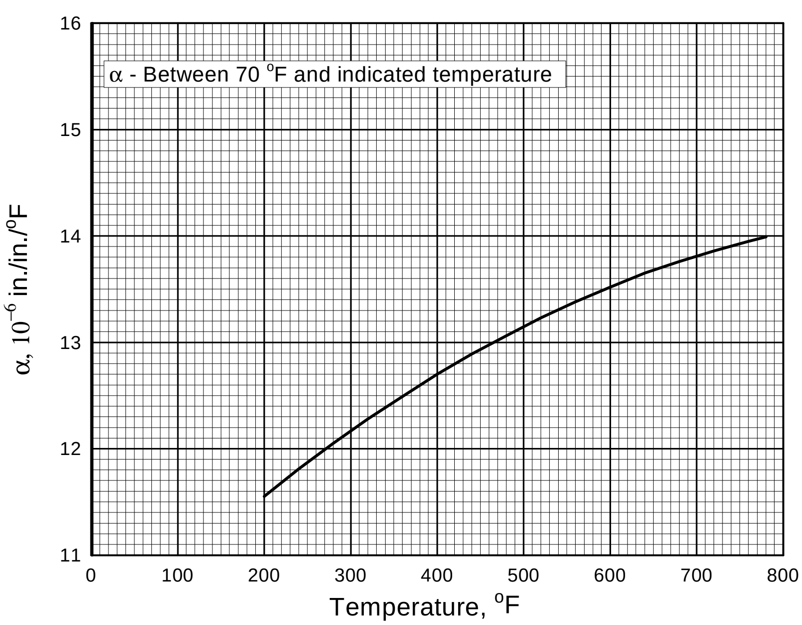

Figure 3.2.11.0. Effect of temperature on the thermal expansion of 2618 aluminum alloy.

Table 3.2.11.0(b). Design Mechanical and Physical Properties of 2618 Aluminum Alloy Die Forging

Specification	AMS-A-22771 and AMS-QQ-A-367
Form	Die forging
Temper	T61
Thickness, in.	$\leq$ 4.000[a]
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	58
T[b]	55
F_{ty}, ksi:	
L	45
T[b]	42
F_{cy}, ksi:	
L	...
T[b]	...
F_{su},	...
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent:	
L	4
T[b]	4
E, 10^3 ksi	10.7
E_c, 10^3 ksi	10.9
G, 10^3 ksi	4.1
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.100
C, Btu/(lb)(°F)	0.23 (at 212°F)
K, Btu/[(hr)(ft^3)(°F)/ft]	90 (at 77°F)
α, 10^{-6} in./in./°F	See Figure 3.2.11.0

a Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.
b T indicates any grain direction not within ±15° of being parallel to the forging flow lines.

Table 3.2.11.0(c). Design Mechanical and Physical Properties of 2618 Aluminum Alloy Hand Forging

Specification	AMS 4132, AMS-A-22771, and AMS-QQ-A-367		
Form	Hand forging		
Temper	T61		
Cross-Sectional Area, in.^{2}	$\leq$ 144		
Thickness,[a] in	< 2.000	2.000-3.000	3.001-4.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	58	57	56
LT	55	55	53
ST	...	52	51
F_{ty}, ksi:			
L	47	46	45
LT	42	42	40
ST	...	42	39
F_{cy}, ksi:			
L	...	...	44
LT	...	...	42
ST	...	...	40
F_{su}, ksi	...	...	33
F_{bru}, ksi:			
(e/D =1.5)	...	...	...
(e/D =2.0)	...	...	106
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	71
e, percent:			
L	7	7	7
LT	5	5	5
ST	...	4	4
E, 10^3 ksi	10.7		
E_c, 10^3 ksi	10.9		
G, 10^3 ksi	4.1		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.100		
C, Btu/(lb)(°F)	0.23 (at 212°F)		
K, Btu/[(hr)(ft^2)(°F)/ft]	90 (at 77°F)		
α, 10^{-6} in./in./°F	See Figure 3.2.11.0		

a When hand forgings are machined before heat treatment, the section thickness at time of heat treatment shall determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table.

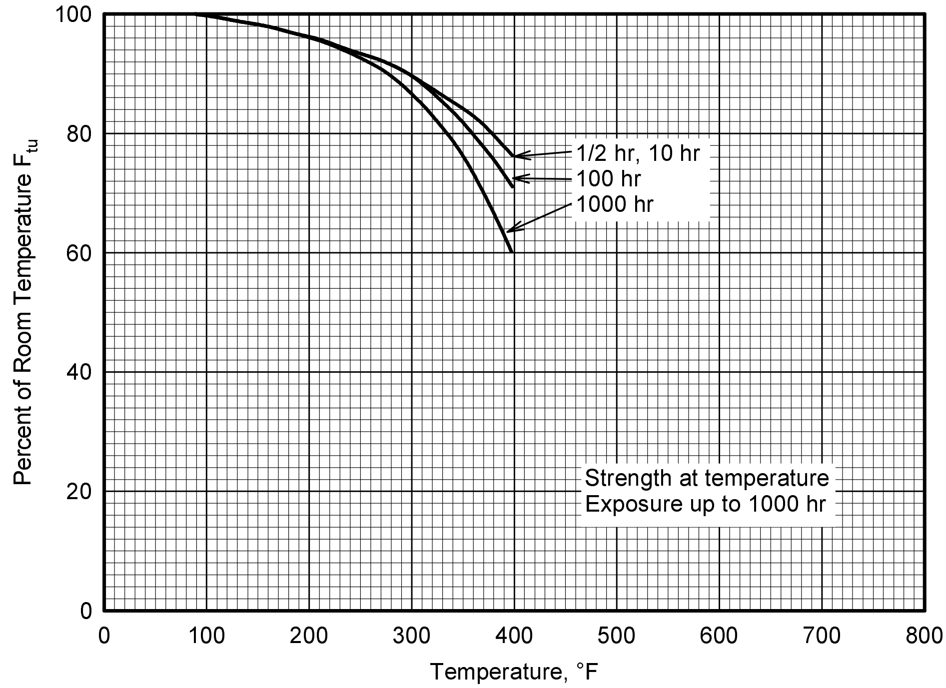

Figure 3.2.11.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 2618-T61 aluminum alloy hand forging.

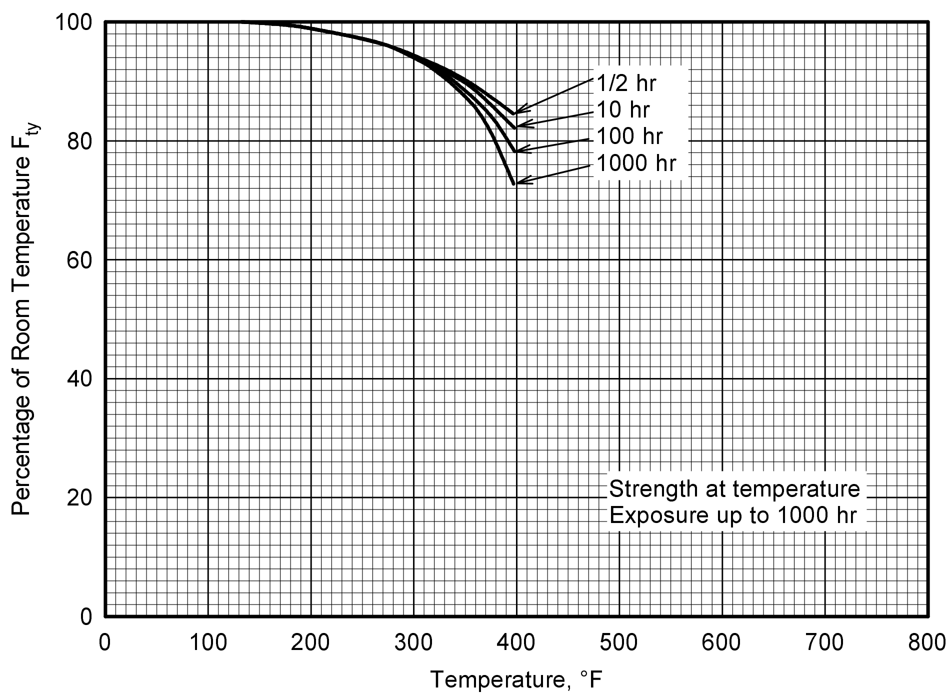

Figure 3.2.11.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2618-T61 aluminum alloy hand forging.

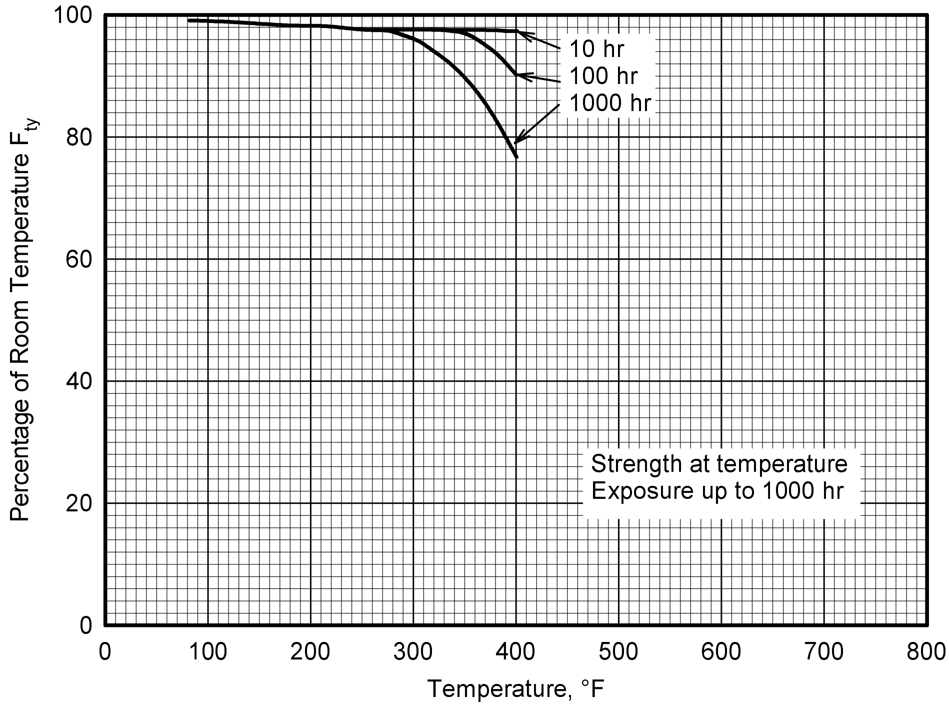

Figure 3.2.11.1.1(c). Effect of exposure at elevated temperatures on room-temperature tensile yield strength (F_{ty}) of 2618-T61 hand forging.

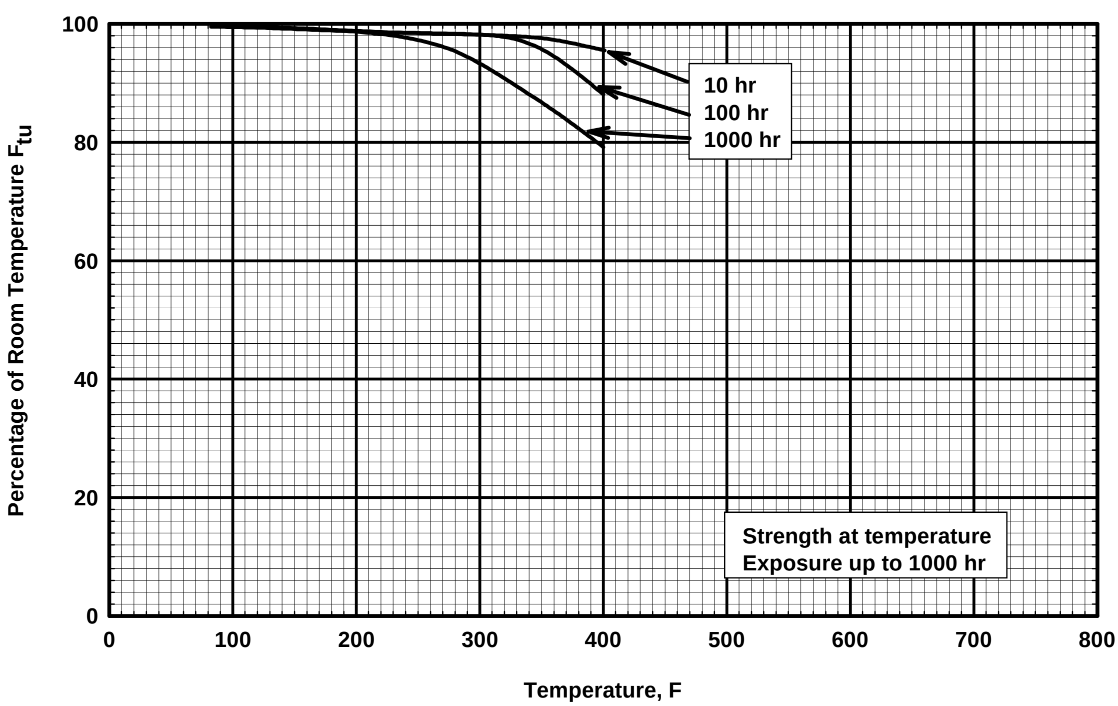

Figure 3.2.11.1.1(d). Effect of exposure at elevated temperatures on room-temperature tensile ultimate strength (F_{tu}) of 2618-T61 hand forging.

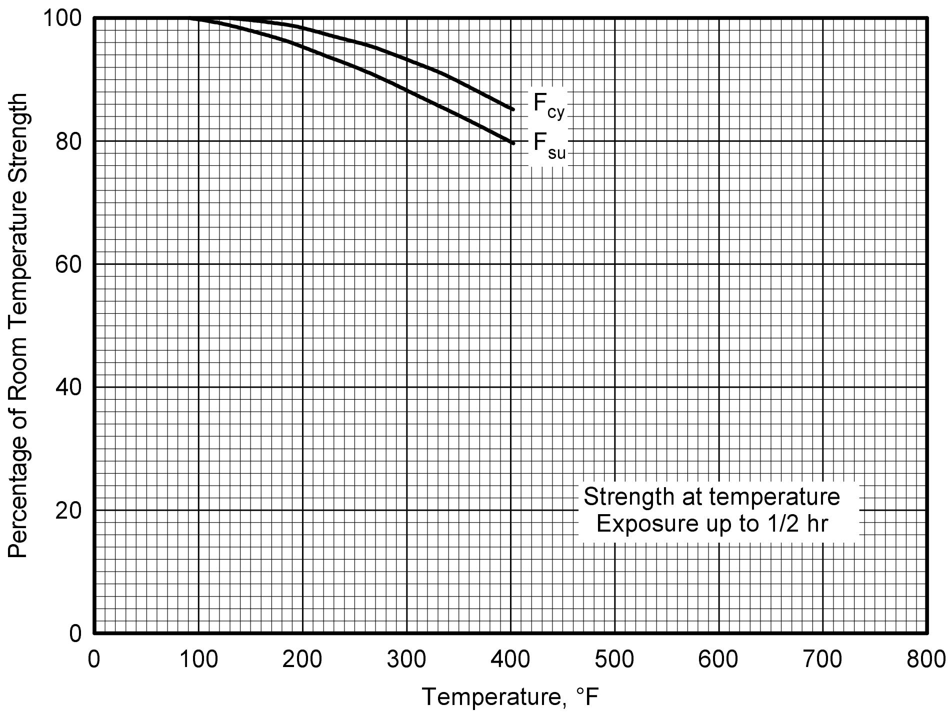

Figure 3.2.11.1.2. Effect of temperature on the compressive yield strength (F_{cy}) and ultimate shear strength (F_{su}) of 2618-T61 aluminum alloy hand forging.

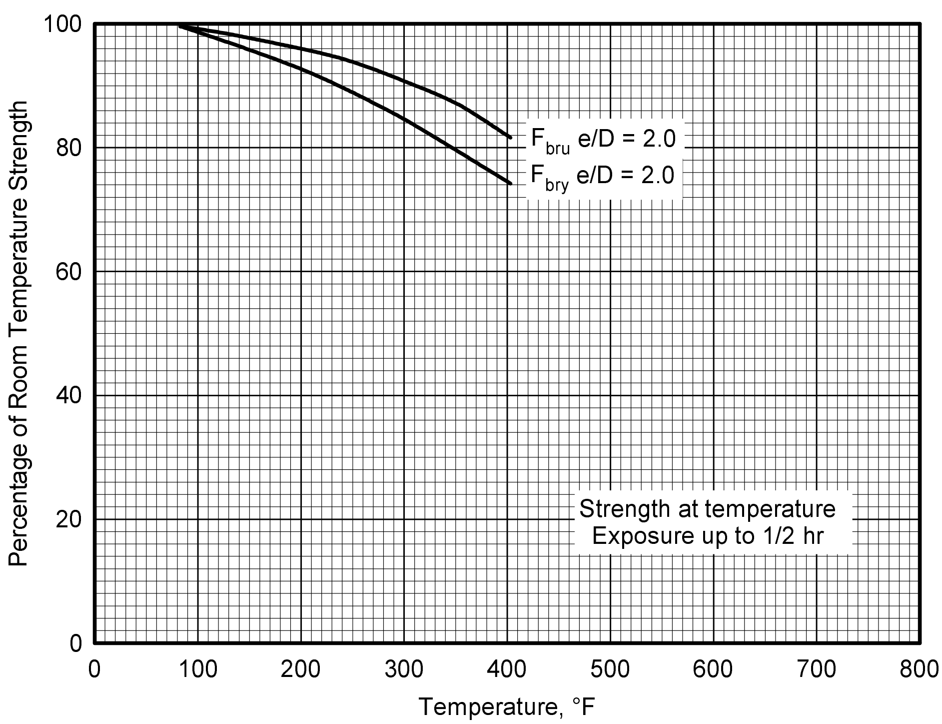

Figure 3.2.11.1.3. Effect of temperature on the bearing ultimate strength (F_{bru}) and bearing yield strength (F_{bry}) of 2618-T61 aluminum alloy hand forging.

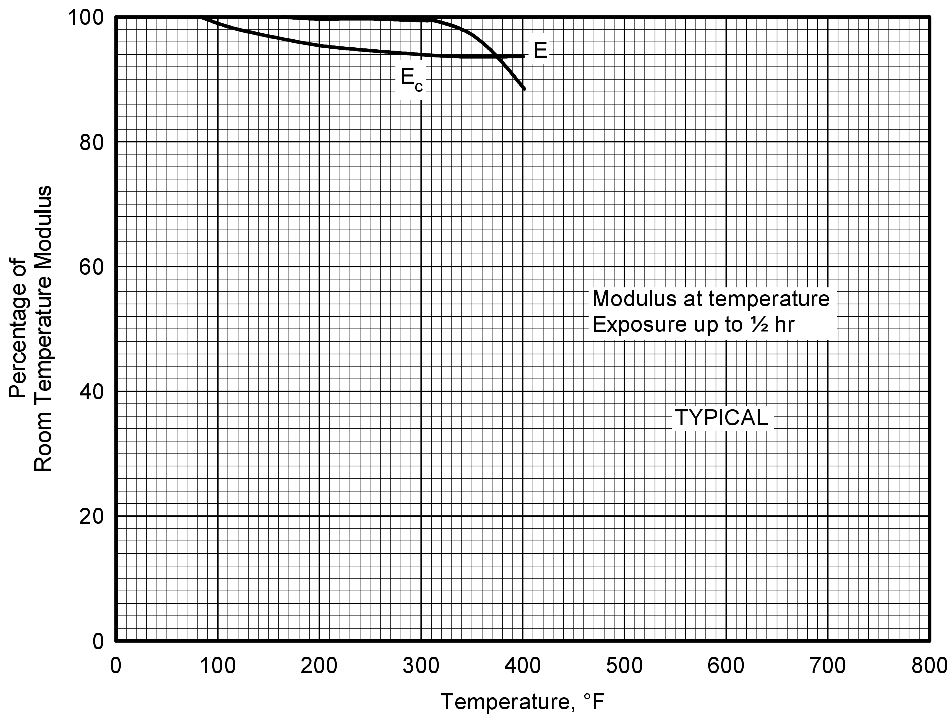

Figure 3.2.11.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 2618-T61 aluminum alloy hand forging.

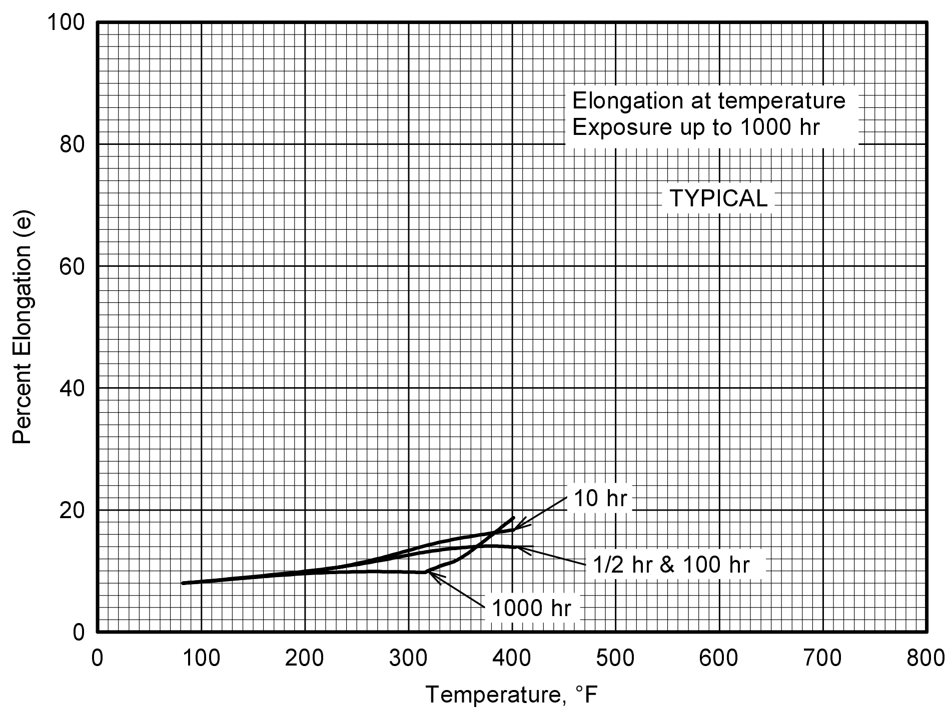

Figure 3.2.11.1.5. Effect of temperature on the elongation (e) of 2618-T61 aluminum alloy hand forging.

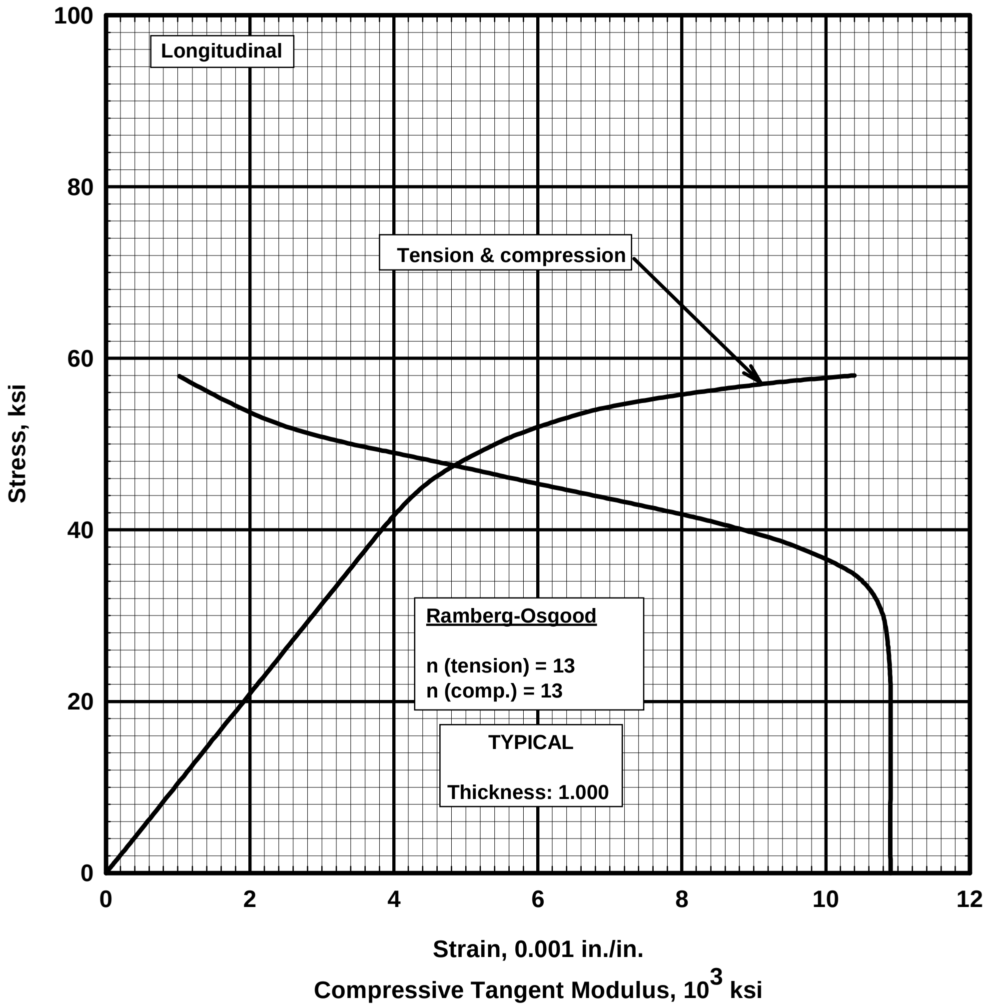

Figure 3.2.11.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 2618-T61 aluminum alloy forged bar at room temperature.

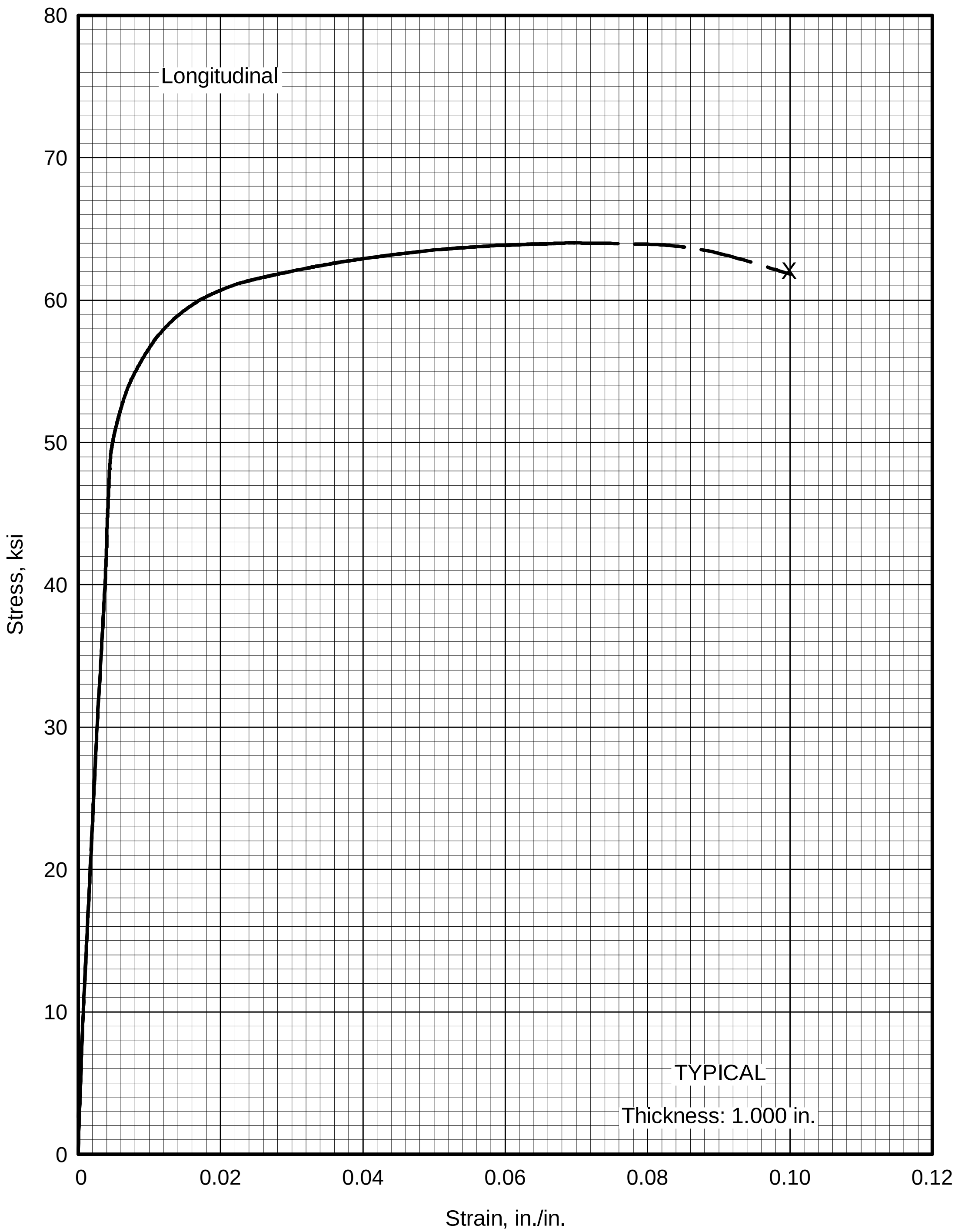

Figure 3.2.11.1.6(b). Typical tensile stress-strain curve (full range) at room temperature for 2618-T61 aluminum alloy forged bar.

Table 3.6.2.0(b_2). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Plate

Specification	AMS 4026 and AMS-QQ-A-250/11				AMS-QQ-A-250/11		AMS 4025, AMS 4027 and AMS-QQ-A-250/11					
Form	Plate											
Temper	T451				T42[a]		T651 and T62[b]					
Thickness, in.	0.250-2.000		2.001-3.000		0.250-1.000	1.001-3.000	0.250-2.000		2.001-3.000		3.001-4.000	4.001-6.000[c]
Basis	A	B	A	B	S	S	A	B	A	B	S	S
Mechanical Properties:												
F_{tu}, ksi:												
L	...	...	...	...	...	...	42	43	...	...	...	...
LT	30	32	30	32	30	30	42	43	42	43	42	40
F_{ty}, ksi:												
L	...	...	...	...	...	...	36	38	...	...	...	...
LT	16	18	16	18	14	14	35	37	35	37	35	35
F_{cy}, ksi:												
L	...	...	...	...	...	...	35	37	...	...	...	...
LT	16	18	...	...	...	...	36	38	...	...	...	...
F_{su}, ksi	20	21	...	...	...	...	27	28	...	...	...	...
F_{bru}, ksi:												
(e/D = 1.5)	48	51	...	...	...	...	67	69	...	...	...	...
(e/D = 2.0)	63	67	...	...	...	...	88	90	...	...	...	...
F_{bry}, ksi:												
(e/D = 1.5)	22	25	...	...	...	...	50	53	...	...	...	...
(e/D = 2.0)	26	29	...	...	...	...	58	61	...	...	...	...
e, percent (S-basis):												
LT	[d]	...	16	...	18	16	[d]	...	6	...	6	6
E, 10^3 ksi	9.9											
E_c, 10^3 ksi	10.1											
G, 10^3 ksi	3.8											
μ	0.33											
Physical Properties:												
ω, lb/in.^{3}	0.098											
C, K, and α	See Figure 3.6.2.0											

a Design allowables were based upon data obtained from testing samples of material, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

b Design allowables were based upon data obtained from testing T651 plate and from testing samples of plate, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

c Properties for this thickness apply only to T651 temper.

d See Table 3.6.2.0(b_3).

Table 3.6.2.0(b_3). Minimum Elongation Values for 6061 Aluminum Alloy Sheet and Plate

Temper and Product	Thickness, inch	Elongation (LT), percent
T4 or T42 sheet	0.010-0.020	14
	0.021-0.249	16
T451 plate	0.250-1.000	18
	1.001-2.000	16
T6 or T62 sheet	0.010-0.020	8
	0.021-0.249	10
T651 or T62 plate	0.250-0.499	10
	0.500-1.000	9
	1.001-2.000	8

Table 3.6.2.0(c_1). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Tube and Pipe

Specification	AMS-WW-T-700/6		AMS 4080, AMS 4082, and AMS-WW-T-700/6	MIL-P-25995	
Form	Drawn tube			Pipe	
Temper	T4	T42[a]	T6[b] and T62	T6	
Wall Thickness, in.	0.025-0.500	0.025-0.500	0.025-0.500	0.049-0.154	0.065-0.687
Outside Diameter, in.	...			<1.000	1.000-12.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	30	30	42	42	38
F_{ty}, ksi:					
L	16	14	35	35	35
F_{cy}, ksi:					
L	14	...	34	34	34
F_{su}, ksi	20	...	27	27	24
F_{bru}, ksi:					
(e/D = 1.5)	48	...	67	67	61
(e/D = 2.0)	63	...	88	88	80
F_{bry}, ksi:					
(e/D = 1.5)	22	...	49	49	49
(e/D = 2.0)	26	...	56	56	56
e, percent:	[c]	[c]	[c]		
L				12	10[d]
E, 10^3 ksi	9.9				
E_c, 10^3 ksi	10.1				
G, 10^3 ksi	3.8				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.098				
C, K, and α	See Figure 3.6.2.0				

a Design allowables were based upon data obtained from testing samples of material, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

b Design allowables were based upon data obtained from testing T6 temper tube and from testing samples of tube, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

c See Table 3.6.2.0(c_2).

d For wall thickness $\leq$0.249 inch, e = 8%.

Table 3.6.2.0(c_2). Minimum Elongation Values for 6061 Aluminum Alloy Tubing

Temper	Wall Thickness, inch	Elongation (L), percent	
		Full-Section Specimen	Cut-Out Specimen
T4 or T42	0.025-0.049	16	14
	0.050-0.259	18	16
	0.260-0.500	20	18
T6 or T62	0.025-0.049	10	8
	0.050-0.259	12	10
	0.260-0.500	14	12

Table 3.6.2.0(f). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Hand Forging

Specification	AMS 4127, AMS 4248, AMS-A-22771, and AMS-QQ-A-367		
Form	Hand forging		
Temper	T6[a] and T652		
Cross-Sectional Area, in.^{2}	≤256		
Thickness, in.	≤2.000	2.001-4.000	4.001-8.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	38	38	37
LT	38	38	37
ST	...	37	35
F_{ty}, ksi:			
L	35	35	34
LT	35	35	34
ST	...	33	32
F_{cy}, ksi:			
L	36	36	35
LT	36	36	35
ST	...	34	33
F_{su}, ksi	25	25	24
F_{bru}, ksi:			
(e/D = 1.5)	61	61	59
(e/D = 2.0)	76	76	74
F_{bry}, ksi:			
(e/D = 1.5)	54	54	53
(e/D = 2.0)	61	61	59
e, percent:			
L	10	10	8
LT	8	8	6
ST	...	5	4
E, 10^3 ksi	9.9		
E_c, 10^3 ksi	10.1		
G, 10^3 ksi	3.8		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.098		
C, K, and α	See Figure 3.6.2.0		

a When hand forgings are machined before heat treatment, the section thickness at time of heat treatment shall determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table.

Table 3.6.2.0(g). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Extruded Rod, Bar, and Shapes

Specification	AMS 4161, AMS 4172, & AMS-QQ-A-200/8	AMS-QQ-A-200/8	AMS 4160 & AMS-QQ-A-200/8	AMS-QQ-A-200/8			
Form	Extruded rod, bar, and shapes						
Temper	T4, T4510, and T4511	T42[a]	T62[a]	T6, T6510, and T6511			
Cross-sectional area, in.^{2}	...	...	...	$\leq$32			
Thickness,[b] in.	$\leq$3.000	All	All	$\leq$1.000		1.001-6.500	
Basis	S	S	S	A	B	A	B
Mechanical Properties:							
F_{tu}, ksi:							
L	26	26	38	38	41	38	41
LT	...	...	...	37	40	33	35
F_{ty}, ksi:							
L	16	12	35	35	38	35	38
LT	...	...	...	33	36	28	31
F_{cy}, ksi:							
L	14	...	...	34	37	34	37
LT	...	...	...	35	38	30	33
F_{su}, ksi	16	...	...	26	28	19	21
F_{bru}[c], ksi:							
(e/D = 1.5)	42	...	...	64	69	52	57
(e/D = 2.0)	55	...	...	82	88	69	74
F_{bry}[c], ksi:							
(e/D = 1.5)	22	...	...	54	58	42	46
(e/D = 2.0)	26	...	...	60	65	50	55
e, percent (S-basis):							
L	16	16	10[d]	10[d]	...	10	...
E, 10^3 ksi	9.9						
E_c, 10^3 ksi	10.1						
G, 10^3 ksi	3.8						
μ	0.33						
Physical Properties:							
ω, lb/in.^{3}	0.098						
C, K, and α	See Figure 3.6.2.0						

a Design allowables were based upon data obtained from testing samples of material, supplied in the O to F temper which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.
b The mechanical properties are to be based upon the thickness at the time of quench.
c Bearing values are "dry pin" values per Section 1.4.7.1.
d For thicknesses $\leq$0.249 inch, e = 8%.

Table 3.6.3.0(b). Design Mechanical and Physical Properties of 6151 Aluminum Alloy Die Forging

Specification	AMS 4125 and AMS-A-22771
Form	Die forging
Temper	T6
Thickness[a], in.	≤4.000
Basis	S
Mechanical Properties:	
F_{tu}, ksi:	
L	44
T[b]	44
F_{ty}, ksi:	
L	37
T[b]	37
F_{cy}, ksi:	
L	39
T[b]	35
F_{su}, ksi	28
F_{bru}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
F_{bry}, ksi:	
(e/D = 1.5)	...
(e/D = 2.0)	...
e, percent:	
L	10
T[b]	6
E, 10^3 ksi	10.1
E_c, 10^3 ksi	10.3
G, 10^3 ksi	3.85
μ	0.33
Physical Properties:	
ω, lb/in.^{3}	0.098
C, Btu/(lb)(°F)	0.23 (at 212°F)
K, Btu/[(hr)(ft^2)(°F)/ft]	100 (at 77°F)
α, 10^{-6} in./in./°F	See Figure 3.6.3.0

a Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.
b T indicates any grain direction not within ±15° of being parallel to the forging flow lines.

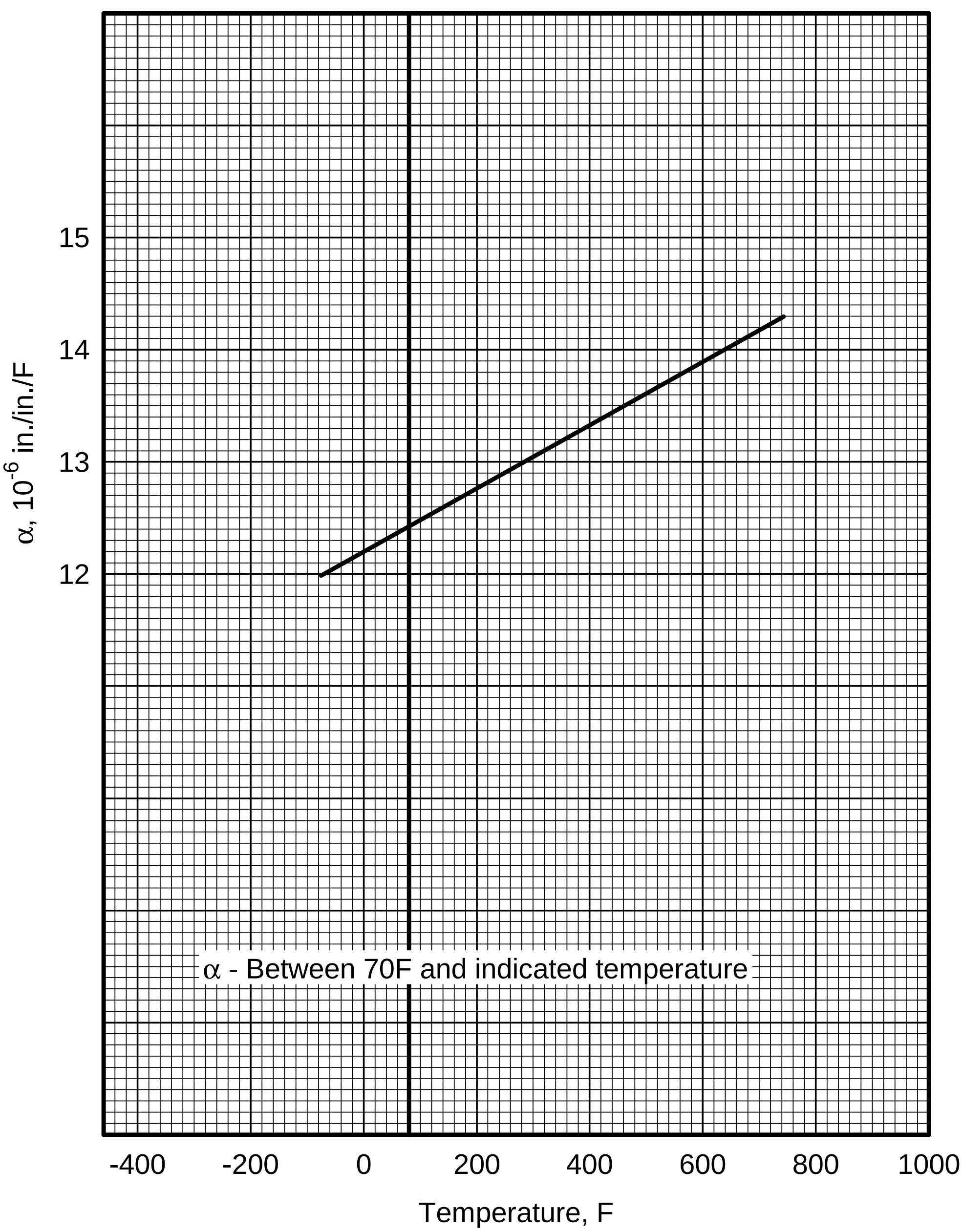

Figure 3.6.3.0. Effect of temperature on the thermal expansion of 6151 aluminum alloy.

3.7 7000 SERIES WROUGHT ALLOYS

The 7000 series of wrought alloys contain zinc as the principal alloying element and magnesium and copper as other major elements. They are available in a wide variety of product forms. They are strengthened principally by solution heat treatment and precipitation hardening, and are among the highest strength aluminum alloys.

The T6-type tempers of these alloys are susceptible to stress-corrosion cracking under certain conditions while the T7-type tempers are more resistant; these alloys should be considered in the light of the corrosion resistance discussed in Sections 3.1.2.3 and 3.1.3.

3.7.1 7010 ALLOY

3.7.1.0 *Comments and Properties* — 7010 is an Al-Zn-Mg-Cu-Zr alloy developed to have a combination of high strength, high resistance to stress-corrosion cracking, and good fracture toughness, particularly in thick sections. The use of zirconium in lieu of chromium provides a low sensitivity to quench, which results in high strength in thick sections. The alloy is available only in plate. Plate, greater than 2½ inches in thickness in the T7451 temper, has static strength equal to or greater than 7075-T651 plate with greater toughness.

Plate in the T7451 temper has a stress-corrosion resistance higher than 7075-T7651. The T73-type temper provides the highest resistance to stress-corrosion for this alloy. The T76-type temper provides for good exfoliation resistance and higher stress-corrosion resistance than T6-type tempers of 7075 and 7178. The T74 type temper provides stress-corrosion and strength characteristics intermediate to those of T76 and T73. Refer to Section 3.1.2.3 for information regarding the resistance of the alloy to stress-corrosion cracking.

Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 7010 are shown in Table 3.7.1.0(a). Room-temperature mechanical properties are shown in Tables 3.7.1.0(b_1) and (b_2).

Table 3.7.1.0(a). Material Specifications for 7010 Aluminum Alloy

Specification	Form
AMS 4205	Plate
AMS 4204	Plate

The temper index for 7010 is as follows:

Section	Temper
3.7.1.1	T7451
3.7.1.2	T7651

3.7.1.1 *T7451 Temper* — Elevated temperature curves for plate are presented in Figure 3.7.1.1.1. Figures 3.7.1.1.6(a) through (d) present stress-strain and tangent-modulus curves for plate.

3.7.1.2 *T7651 Temper* — Figures 3.7.1.2.6(a) through (d) present stress-strain and tangent-modulus curves for plate.

Table 3.7.1.0(b_1). Design Mechanical and Physical Properties of 7010 Aluminum Alloy Plate

Specification	AMS 4205									
Form	Plate									
Temper	T7451									
Thickness, in.	0.250-1.000	1.001-2.000	2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000	
Basis	S	S	A	B	A	B	A	B	A	B
Mechanical Properties:										
F_{tu}, ksi:										
L	71	71	70	72	70	71	68[a]	71	68	70
LT	72	72	71	72	70	72	69[a]	71	67[a]	71
ST	...	...	66	68	66	68	65[a]	67	63[a]	67
F_{ty}, ksi:										
L	62	62	60	62	60	62	59	61	57[a]	61
LT	62	62	60	62	59	61	58	60	57[a]	60
ST	...	...	55	57	54	56	53	55	52	54
F_{cy}, ksi:										
L	61	61	59	61	58	60	57	59	56	59
LT	63	63	62	64	61	63	60	62	59	63
ST	...	...	61	63	60	62	59	61	58	61
F_{su}, ksi	41	41	42	42	42	43	42	43	41	43
F_{bru}[b], ksi:										
(e/D = 1.5)	100	101	101	102	100	103	100	103	97	103
(e/D = 2.0)	127	129	130	132	130	134	129	133	126	133
F_{bry}[b], ksi:										
(e/D = 1.5)	81	82	81	84	81	84	81	84	80	84
(e/D = 2.0)	94	97	97	100	98	101	98	101	97	102
e, percent (S-basis):										
L	9	9	9	...	9	...	9	...	8	...
LT	6	6	6	...	6	...	5	...	5	...
ST	...	...	2.5	...	2	...	2	...	2	...
E, 10^3 ksi	10.2									
E_c, 10^3 ksi	10.6									
G, 10^3 ksi	3.9									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.102									
C, Btu/(lb)(°F)	0.21 (at 214°F)									
K, Btu/[(hr)(ft^2)(°F)/ft]	95 (at 99°F)									
α, 10^{-6} in./in./°F	13.0 (68-212°F)									

a S-basis values. The rounded T_{99} values are as follows: for 4.001-5.000-inch thickness, F_{tu}(L) = 69, F_{tu}(LT) = 70, and F_{tu}(ST) = 66; for 5.001-6.000-inch thickness, F_{tu}(LT) = 69, F_{tu}(ST) = 65, F_{ty}(L) = 59, and F_{ty}(LT) = 58.

b See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

3.7.2 7040-T7451

3.7.2.0 ***Comments and Properties*** — 7040 alloy is an Al-Mg-Zn-Cu-Zr alloy developed to provide a higher strength/toughness compromise than the currently available 7010 and 7050 alloys, in particular in heavy gauge plates up to 8.5 inch thickness. The use of a desaturated chemical composition in Mg and Cu together with a very close control of the Zr content and impurities, provide 7040 with a much lower quench sensitivity than that of 7050, resulting in high strength and toughness properties in very thick sections.

7040-T7451 plates are particularly suited for structures in which high strength, high toughness and good corrosion resistance are the major requirements. Parts such as integrally machined spars, ribs and main fuselage frames can benefit from this outstanding property combination.

7040 is available in the form of plates, in the thickness range 3.0 to 8.5 inches.

Manufacturing Considerations — Due to tight control of residual stress level, the 7040 plates exhibit a superior dimensional stability, thus offering a cost-efficient alternative to rolled or forged parts which require distortion corrections after machining.

Refer to Section 3.1.3.4 for comments regarding the weldability of this alloy.

Specifications and Properties — Material specifications are shown in Table 3.7.2.0(a). Room temperature properties are shown in Table 3.7.2.0(b_1). Figure 3.7.2.0 shows the effect of temperature on tensile properties.

Table 3.7.2.0(a). Material Specifications for 7040-T7451 Alloy Plate

Specification	Form
AMS 4211	Plate

Table 3.7.2.0(b_1). Design Mechanical and Physical Properties of 7040-T7451 Aluminum Alloy Plate

Specification	AMS 4211											
Form	Plate											
Temper	T7451											
Thickness, in.	3.001-4.000		4.001-5.000		5.001-6.000		6.001 -7.000		7.001 -8.000		8.001 -8.500	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi:												
L	72	72	71	72	70[a]	71	69	70	68[b]	70	68[c]	70
LT	72[d]	74	71[e]	73	70[a]	72	69	70	68[b]	69	68	69
ST	69	70	68[e]	70	68	69	66	67	66	67	66	67
F_{ty}, ksi:												
L	62[d]	65	62[e]	64	62[a]	64	62	62	61	62	61	63
LT	62[d]	65	62[e]	65	61[a]	63	60	62	60	61	59	61
ST	59[d]	61	58[e]	61	58[a]	61	57	58	57	58	56	58
F_{cy}, ksi:												
L	60	63	60	62	59	61	58	60	59	60	59	61
LT	64	67	64	67	63	66	62	64	62	64	61	63
ST	63	66	63	66	62	65	61	63	61	63	60	63
F_{su}, ksi	45	47	44	46	44	45	43	44	43	44	43	44
F_{bru}[f], ksi:												
(e/D = 1.5)	114	117	112	115	110	114	108	110	105	108	105	106
(e/D = 2.0)	145	150	143	147	140	145	137	140	134	136	133	134
F_{bry}[f], ksi:												
(e/D = 1.5)	93	97	93	97	92	96	90	93	90	92	88	91
(e/D = 2.0)	114	119	114	119	112	117	110	113	110	113	108	112
e, percent (S-basis):												
L	9	...	9	...	8	...	7	...	6	...	6	...
LT	6	...	5	...	4	...	4	...	4	...	4	...
ST	3	...	3	...	3	...	3	...	3	...	3	...
E, 10^3 ksi	10.4											
E_c, 10^3 ksi	10.6											
G, 10^3 ksi	3.9											
μ	0.33											
Physical Properties:												
ω, lb/in.^{3}	0.102											
C, Btu/(lb)(°F)	0.23											
K, Btu/[(hr)(ft^2)(°F)/ft]	91											
α, 10^{-6} in./in./°F	12.8											

a S-basis values. Rounded T_{99} values are as follows: F_{tu}(L) = 71 ksi; F_{tu}(LT) = 71 ksi; F_{ty}(L) = 63 ksi; F_{ty}(LT) = 62 ksi; and F_{ty}(ST) = 59 ksi.
b S-basis values. Rounded T_{99} values are as follows: F_{tu}(L) = 69 ksi; F_{tu}(LT) = 69 ksi.
c S-basis values. Rounded T_{99} values are as follows: F_{tu}(L) = 69 ksi.
d S-basis values. Rounded T_{99} values are as follows: F_{tu}(LT) = 73 ksi; F_{ty}(L) = 64 ksi; F_{ty}(LT) = 64 ksi; and F_{ty}(ST) = 60 ksi.
e S-basis values. Rounded T_{99} values are as follows: F_{tu}(LT) = 72 ksi; F_{tu}(ST) = 69 ksi; F_{ty}(L) = 63 ksi; and F_{ty}(LT) = 63 ksi, F_{ty}(ST) = 59 ksi.
f See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

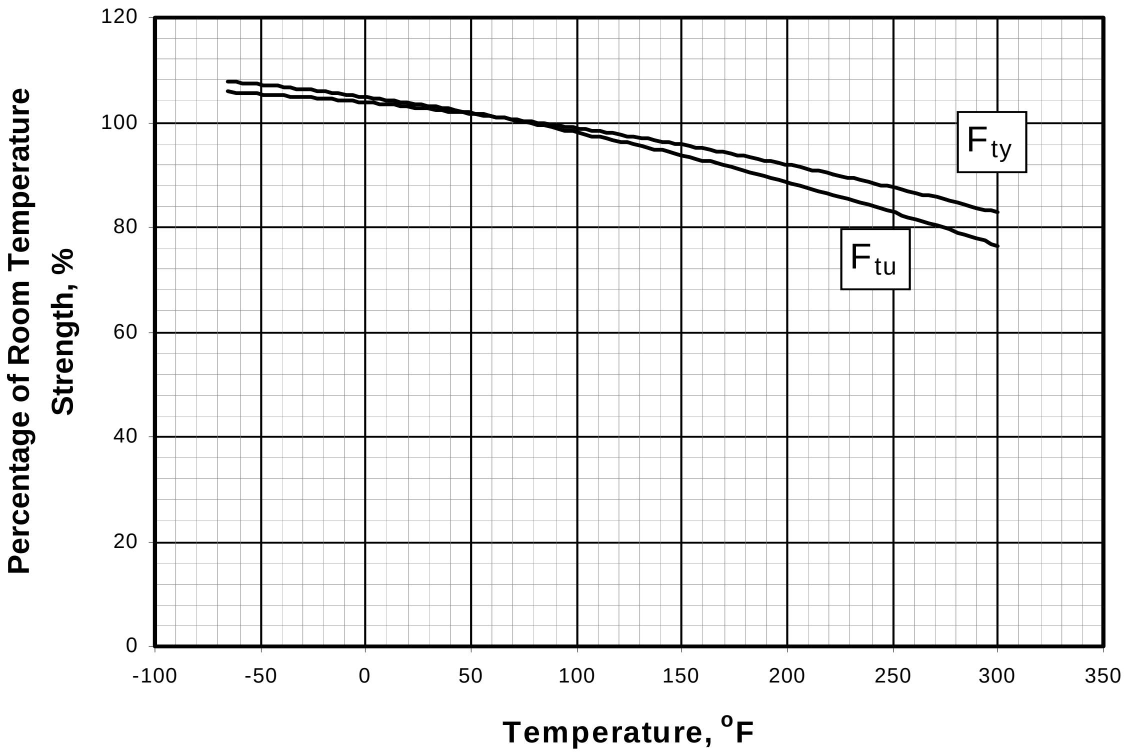

Figure 3.7.2.0 Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 7040-T7451aluminum alloy plate, T/4 location.

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3.7.3 7049/7149 ALLOY

3.7.3.0 *Comments and Properties* — Alloy 7049/7149 is available in the form of die forging, hand forging, plate, and extrusion. Alloy 7149 contains lower residual iron and silicon content than 7049. The T73XX temper provides good static strength with high resistance to stress-corrosion cracking. The fatigue strength of the T73XX temper is about equal to that of 7075-T6, while the toughness is somewhat higher. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloys to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloys.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 7049/7149 aluminum alloy are presented in Table 3.7.3.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.7.3.0(b) through (e).

Table 3.7.3.0(a). Material Specifications for 7049/7149 Aluminum Alloy

Specification	Form
AMS-QQ-A-367 (7049)	Forging
AMS 4111 (7049)	Forging
AMS 4320 (7149)	Forging
AMS 4157 (7049)	Extrusion
AMS-A-22771	Forging
AMS 4200 (7049)	Plate
AMS 4343 (7149)	Extrusion

The temper index for 7049/7149 is as follows:

Section	Temper
3.7.3.1	T73 and T73511

3.7.3.1 *T73 and T73511 Tempers* — Figure 3.7.3.1.1 presents elevated temperature curves for various products. Figures 3.7.3.1.6(a) through (g) present tensile and compressive stress-strain and tangent-modulus curves. Fatigue data for 7049-T73 die and hand forgings are shown in Figures 3.7.3.1.8(a) through (g).

Table 3.7.3.0(b). Design Mechanical and Physical Properties of 7049 Aluminum Alloy Plate

Specification	AMS 4200							
Form	Plate							
Temper	T7351							
Thickness, in.	0.750-1.000	1.001-1.500	1.501-2.000	2.001-2.500	2.501-3.000	3.001-4.000	4.001-4.500	4.501-5.000
Basis	S	S	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	...	...	72	72	71	70	68	68
LT	74	73	73	73	72	70	68	68
ST	...	...	69	69	68	65	63	63
F_{ty}, ksi:								
L	...	...	64	63	62	60	58	58
LT	65	64	64	63	62	60	58	58
ST	...	...	59	58	57	56	54	54
F_{cy}, ksi:								
L	...	...	64	63	62	60	58	...
LT	...	...	69	68	67	64	62	...
ST	...	...	69	68	67	64	62	...
F_{su}, ksi	...	...	41	41	41	39	38	...
F_{bru}[a], ksi:								
(e/D = 1.5)	...	...	...	114	112	109	106	...
(e/D = 2.0)	...	...	...	146	144	140	136	...
F_{bry}[a], ksi:								
(e/D = 1.5)	...	...	...	91	89	86	83	...
(e/D = 2.0)	...	...	...	106	104	101	97	...
e, percent:								
L	...	...	...	...	...	6	6	5
LT	8	8	7	6	6	5	5	5
ST	...	...	...	...	...	2	2	2
E, 10^3 ksi	10.1							
E_c, 10^3 ksi	10.4							
G, 10^3 ksi	3.9							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.103							
C, Btu/(lb)(°F) ...	0.23 (at 212°F)							
K, Btu/[(hr)(ft^2)(°F)/ft]	89 (at 77°F)							
α, 10^{-6} in./in./°F ...	13.0 (RT to 212°F)							

a Bearing values are “dry pin” values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.3.0(c). Design Mechanical and Physical Properties of 7049/7149 Aluminum Alloy Die Forging

Specification	AMS-QQ-A-367, AMS 4111, AMS 4320, and AMS-A-22771									
Form	Die forging									
Temper	T73[a]									
Thickness[b], in.	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000		4.001-5.000	
Basis	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:										
F_{tu}, ksi:										
L	71	74	70	73	69	72	68	71	67	70
T[c] (S-basis)	71[d]	...	70[d]	...	70[d]	...	70[d]	...	68[d]	...
F_{ty}, ksi:										
L	60	64	59	63	58	61	57	60	55	59
T[c] (S-basis)	61[d]	...	60[d]	...	60[d]	...	60[d]	...	58[d]	...
F_{cy}, ksi:										
L	62	66	61	65	60	63	59	62	57	61
ST	56	60	55	59	54	57	53	56	51	55
F_{su}, ksi	40	41	39	41	39	40	38	40	37	39
F_{bru}[e], ksi:										
(e/D = 1.5)	100	105	99	103	98	102	96	100	95	99
(e/D = 2.0)	132	138	130	136	128	134	126	132	125	130
F_{bry}[e], ksi:										
(e/D = 1.5)	76	82	75	80	74	78	73	76	70	75
(e/D = 2.0)	93	99	91	97	90	94	88	93	85	91
e, percent (S-basis):										
L	7	...	7	...	7	...	7	...	7	...
T[c]	3	...	3	...	3	...	2	...	2	...
E, 10^3 ksi	10.2									
E_c, 10^3 ksi	10.7									
G, 10^3 ksi	3.9									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.103									
C, Btu/(lb)(°F) ...	0.25 (at 212°F)									
K, Btu/[(hr)(ft^2)(°F)/ft]	89 (at 77°F)									
α, 10^{-6} in./in./°F ..	13.0 (RT to 212°F)									

a Design values were based upon data obtained from testing T73 die forgings, heat treated by suppliers and supplied in T73 temper.
b Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.
c T indicates any grain direction not within ±15° of being parallel to the forging flow lines. F_{cy}(T) values are based upon short transverse (ST) test data.
d Specification value. T tensile properties are presented on an S-basis only.
e Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.3.0(d). Design Mechanical and Physical Properties of 7049/7149 Aluminum Alloy Hand Forging

Specification	AMS-QQ-A-367, AMS 4111, AMS 4320, and AMS-A-22771		
Form	Hand forging		
Temper	T73		
Thickness[a], in.	2.001-3.000	3.001-4.000	4.001-5.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	71	69	67
LT	71	69	67
ST	69	67	66
F_{ty}, ksi:			
L	61	59	56
LT	59	57	56
ST	58	56	55
F_{cy}, ksi:			
L	60	58	57
LT	61	59	57
ST	61	59	58
F_{su}, ksi:			
L	42	41	39
LT	41	39	38
ST	41	40	39
F_{bru}[b], ksi:			
(e/D = 1.5)	102	100	97
(e/D = 2.0)	134	130	126
F_{bry}[b], ksi:			
(e/D = 1.5)	81	79	77
(e/D = 2.0)	96	92	91
e, percent:			
L	9	8	7
LT	4	3	3
ST	3	2	2
E, 10^3 ksi	10.2		
E_c, 10^3 ksi	10.6		
G, 10^3 ksi	3.9		
μ	0.33		
Physical Properties:			
ω, lb./in.^{3}	0.103		
C, Btu/(lb)(°F)	0.23 (at 212°F)		
K, Btu/[(hr)(ft^2)(°F)/ft]	89 (at 77°F)		
α, 10^{-6} in./in./°F	13.0 (RT to 212°F)		

a When hand forgings are machined before heat treatment, section thickness at time of heat treatment shall determine minimum mechanical properties as long as original (as-forged) thickness does not exceed maximum thickness for the alloy as shown in the table. The maximum cross-section area of hand forgings is 256 sq. in.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.3.0(e). Design Mechanical and Physical Properties of 7049/7149 Aluminum Alloy Extrusion

Specification	AMS 4157 and AMS 4343		
Form	Extrusion		
Temper	T73511		
Thickness,[a] in.	≤ 2.499	2.500-2.999	3.000-5.000
Basis	S	S	S
Mechanical Properties:			
F_{tu}, ksi:			
L	74	74	72
LT	70	70	68
ST	...	70	68
F_{ty}, ksi:			
L	64	64	62
LT	60	60	58
ST	...	60	58
F_{cy}, ksi:			
L	65	65	63
LT	...	...	...
ST	...	...	...
F_{su}, ksi	40	40	39
F_{bru}[b], ksi:			
(e/D = 1.5)	110	110	107
(e/D = 2.0)	144	144	140
F_{bry}[b], ksi:			
(e/D = 1.5)	85	85	83
(e/D = 2.0)	105	105	101
e, percent:			
L	7	7	7
LT	5	5	5
ST	...	5	5
E, 10^3 ksi	10.5		
E_c, 10^3 ksi	11.0		
G, 10^3 ksi	4.0		
μ	0.33		
Physical Properties:			
ω, lb/in.^{3}	0.103		
C, Btu/(lb)(°F)	0.23 (at 212°F)		
K, Btu/[(hr)(ft^2)(°F)/ft] ..	89 (at 77°F)		
α, 10^{-6} in./in./°F	13.0 (RT to 212°F)		

a The mechanical properties are to be based upon the thickness at the time of quench.
b Bearing values are “dry pin” values per Section 1.4.7.1.

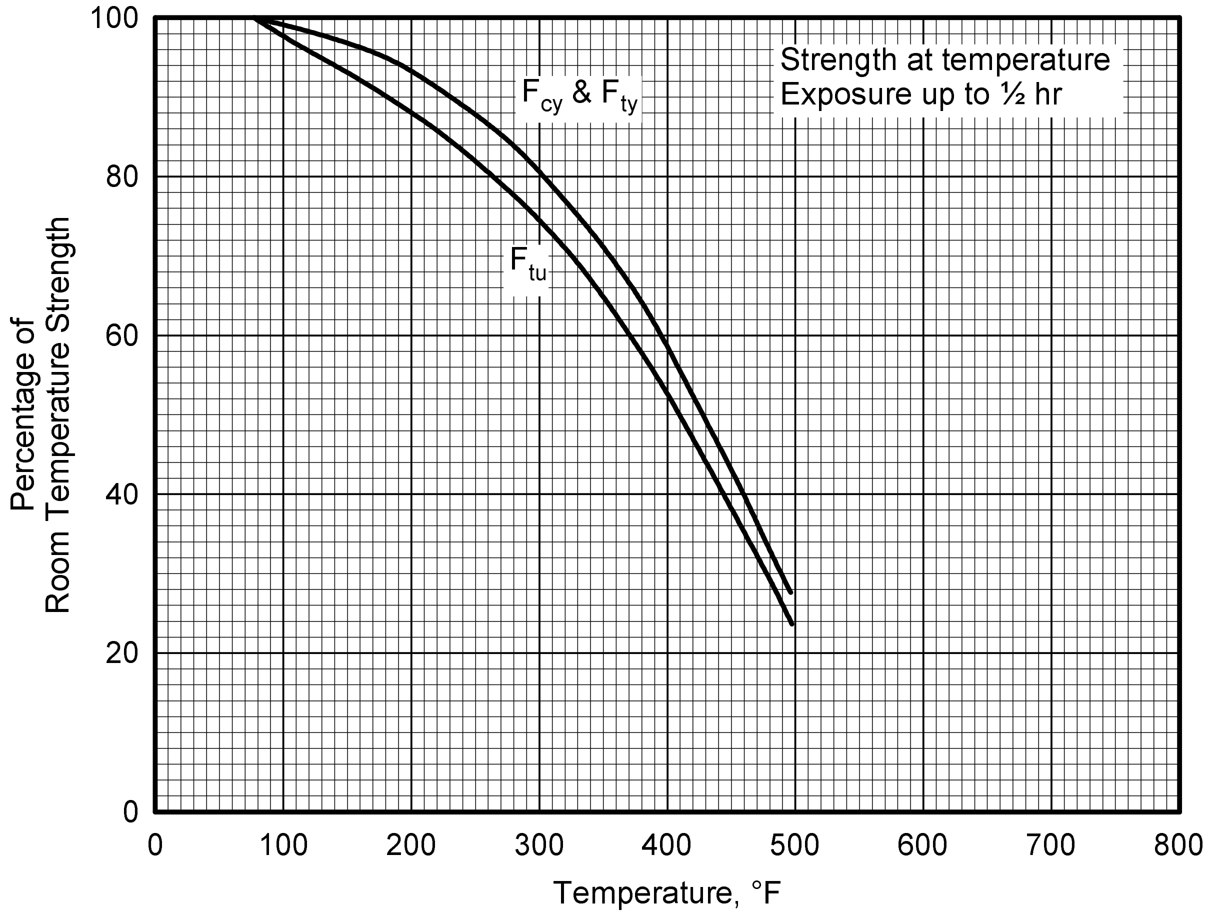


Figure 3.7.3.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}), the tensile yield strength (F_{ty}), and the compressive yield strength (F_{cy}) of 7049-T7351 plate, 7049/7149-T73 hand forging, and 7049/7149-T7351 extrusion.

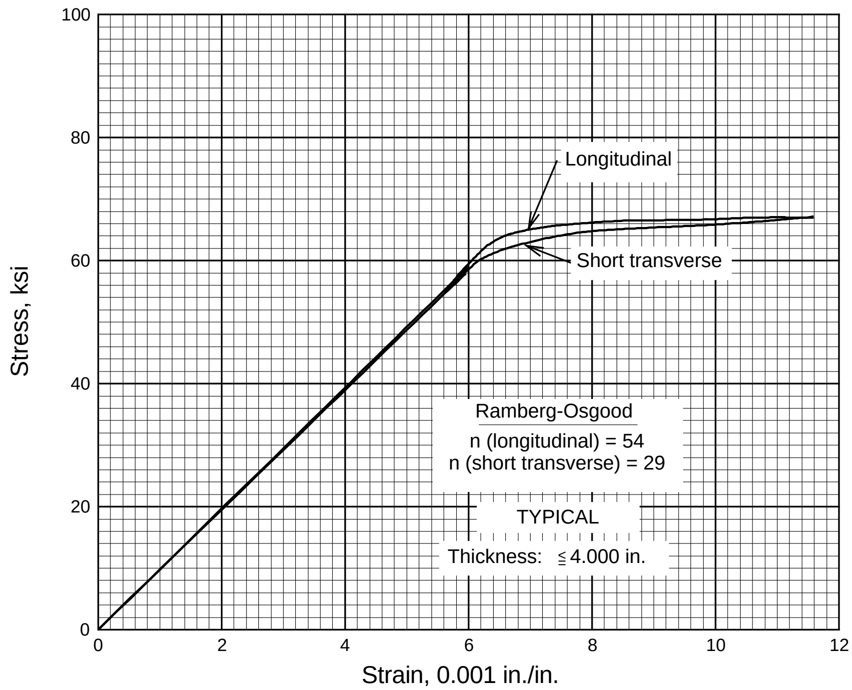


Figure 3.7.3.1.6(a). Typical tensile stress-strain curves for 7049/7149-T73 aluminum alloy die forging at room temperature.

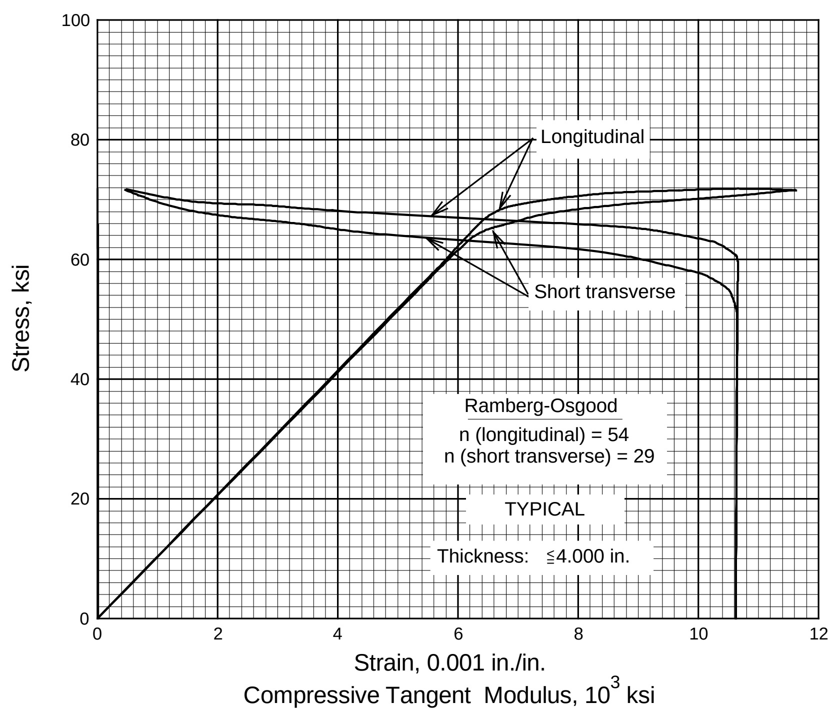


Figure 3.7.3.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7049/7149-T73 aluminum alloy die forging at room temperature.

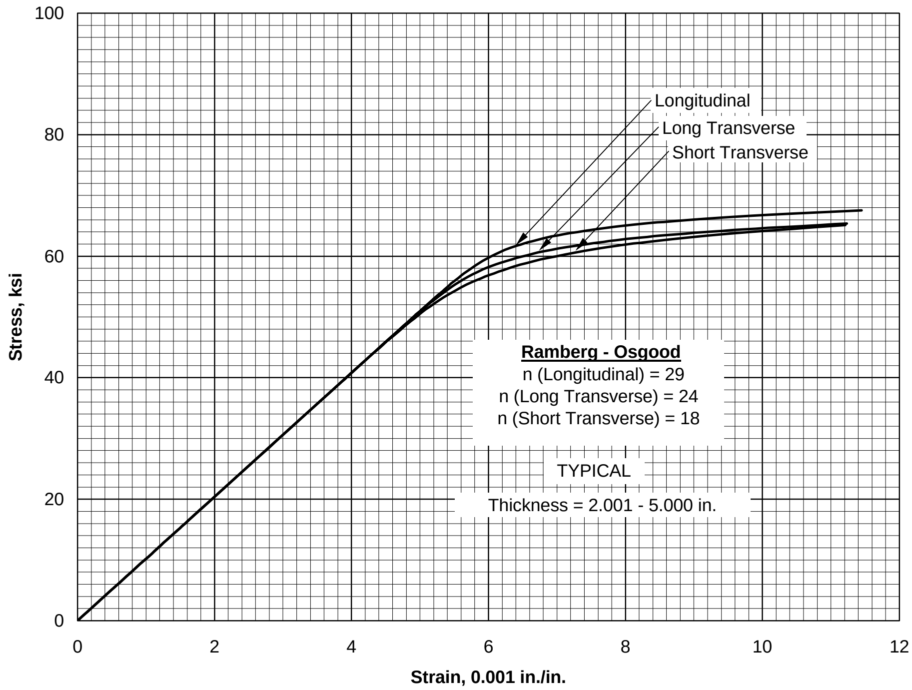


Figure 3.7.3.1.6(c). Typical tensile stress-strain curves for 7049/7149-T73 aluminum alloy hand forging at room temperature.

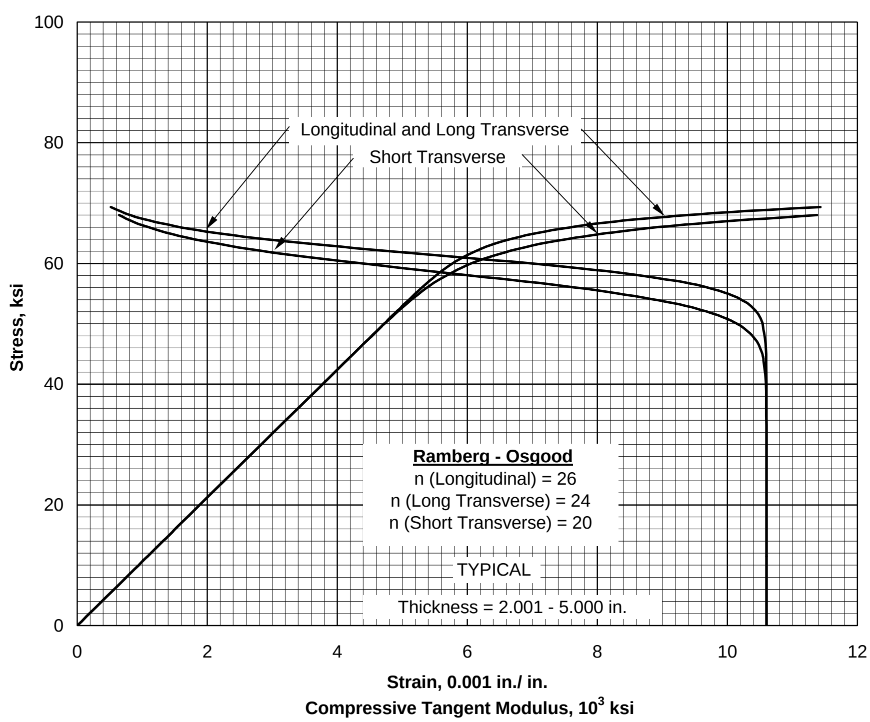


Figure 3.7.3.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7049/7149-T73 aluminum alloy hand forging at room temperature.

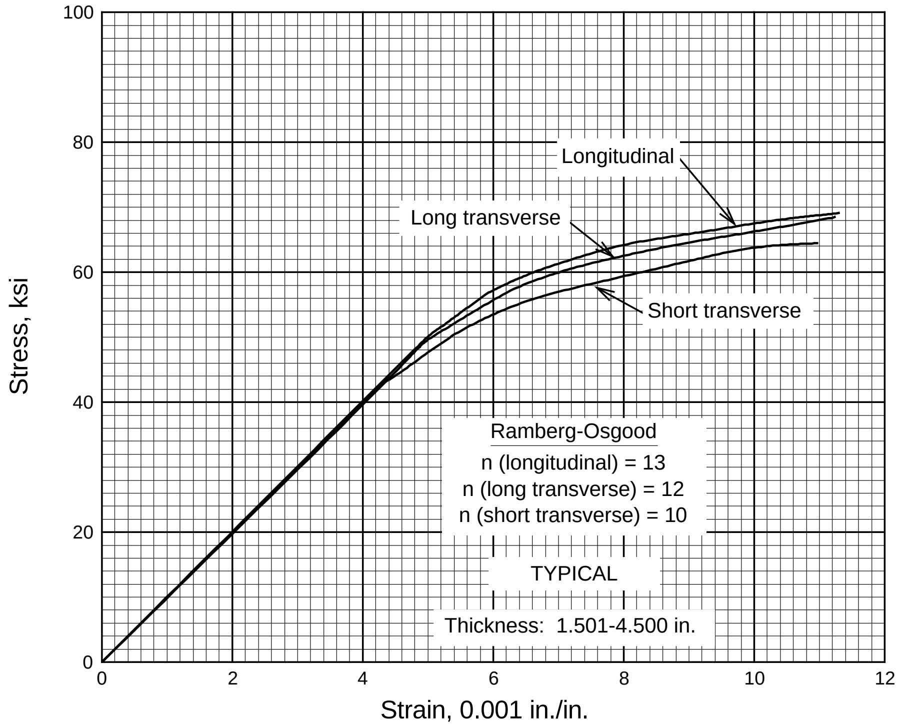


Figure 3.7.3.1.6(e). Typical tensile stress-strain curves for 7049-T7351 aluminum alloy plate at room temperature.

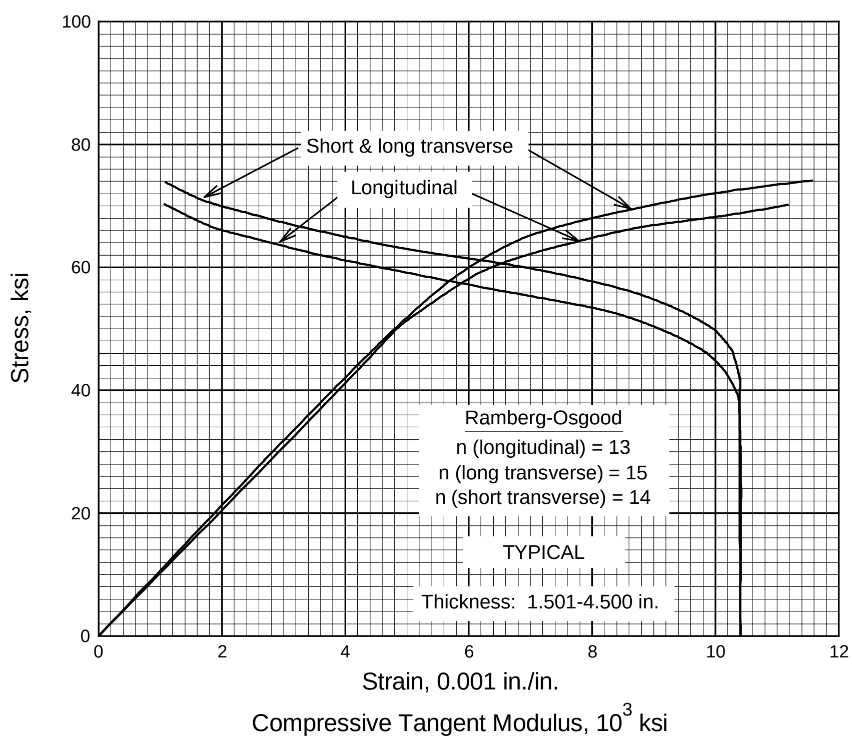


Figure 3.7.3.1.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for 7049-T7351 aluminum alloy plate at room temperature.

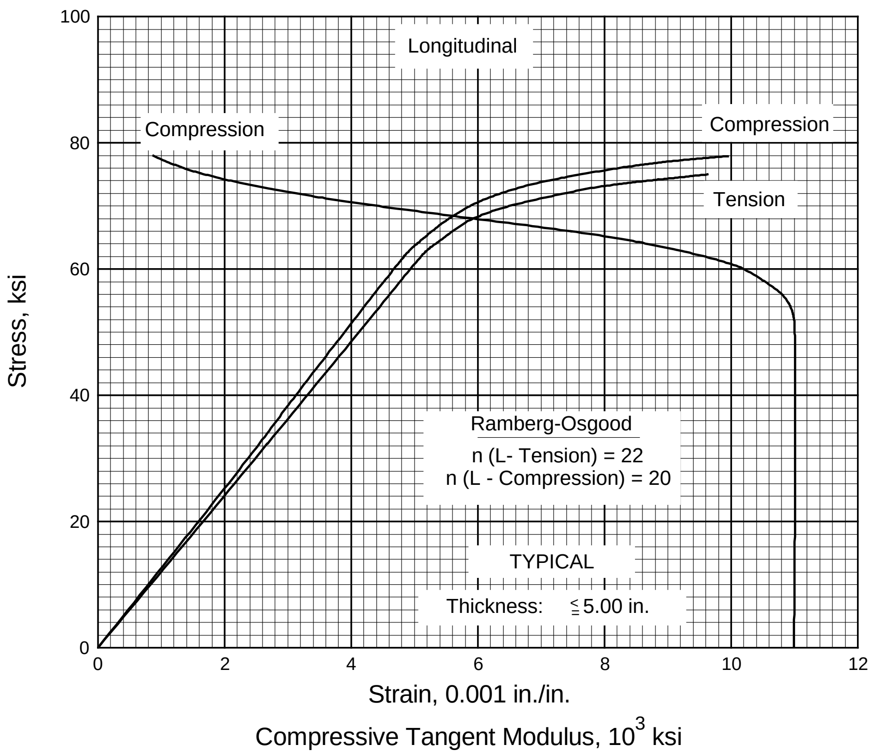


Figure 3.7.3.1.6(g). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7049/7149-T73511 extrusion at room temperature.

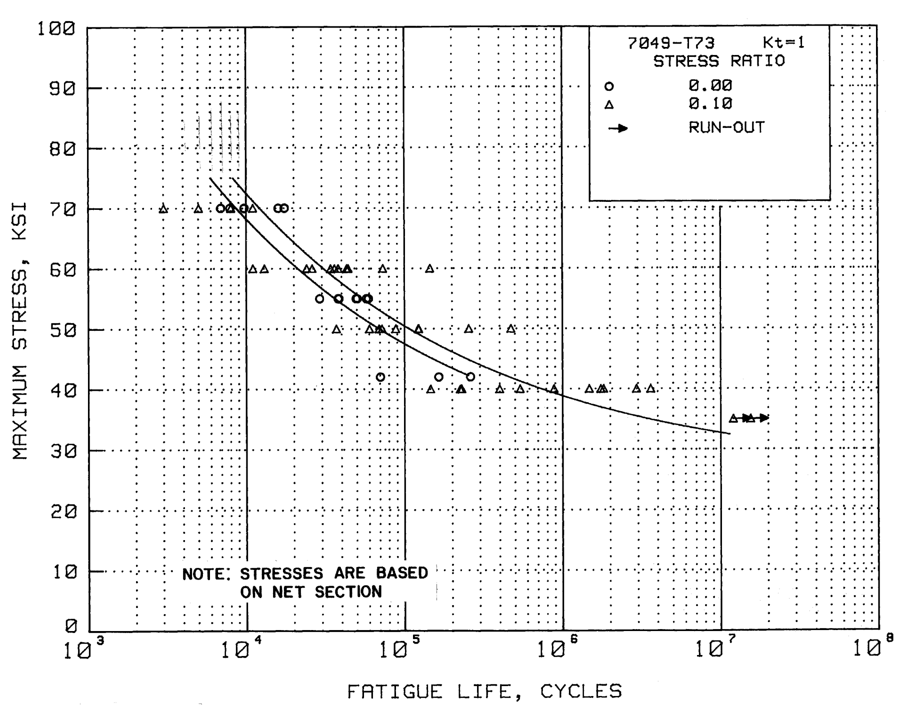


Figure 3.7.3.1.8(a). Best-fit S/N curves for unnotched 7049-T73 die and hand forgings, at room temperature, longitudinal and long-transverse directions.

Correlative Information for Figure 3.7.3.1.8(a)

Product Form: Die forging, 3 and 4.5-inches thick. Hand forging, 2, 3, 4, and 5 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
(L)	78	70	RT
(LT)	74	65	RT

Specimen Details: Unnotched
Uniform Gage, 0.200-inch net diameter (Ref. a)
Hourglass, 0.225-inch net diameter (Ref. b)
3.000-inch test section radius
Hourglass, 0.300-inch net diameter (Ref. d)
9.875-inch test section radius

Surface Condition:
Longitudinally polished to 4 RMS finish or better (Ref. a)
Unspecified (Ref. b)

References: 3.7.3.1.8(a), (b), and 3.2.6.1.9(d)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Lab air

No. of Heats/Lots: 6

Stress Life Equation:
Log N_f = 9.95-3.62 log (S_{eq}-24.2)
$S_{eq} = S_{max}$ $(1-R)^{0.57}$
Std. Error of Estimate, Log (Life) = 0.346
Standard Deviation, Log (Life) = 0.736
R^2 = 78%

Sample Size = 50

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

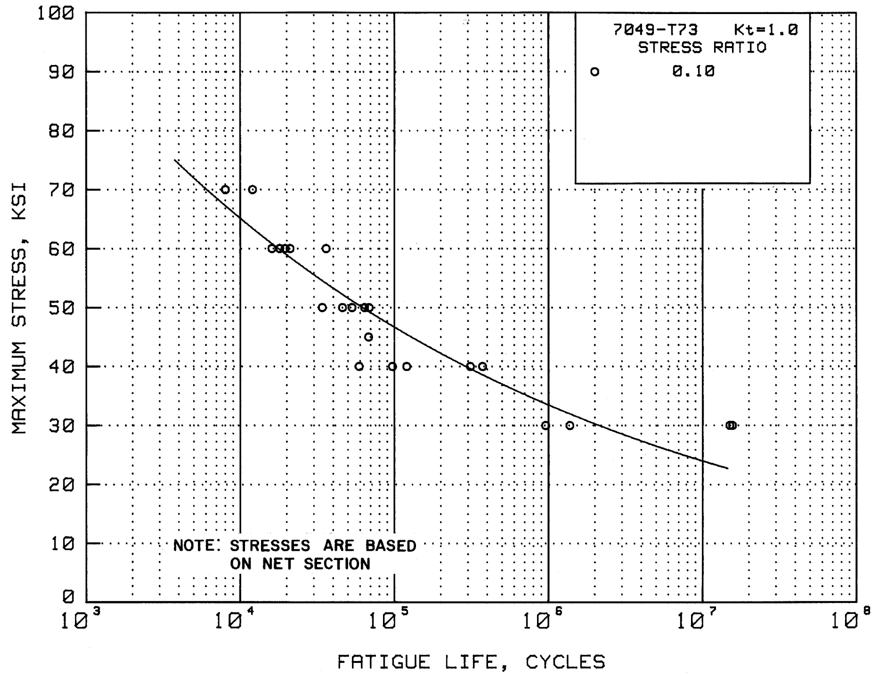


Figure 3.7.3.1.8(b). Best-fit curves for unnotched 7049-T73 die forging, at room temperature, short transverse direction.

Correlative Information for Figure 3.7.3.1.8(b)

Product Form: Die forging, 3-inches thick

Properties:

	TUS, ksi	TYS, ksi	Temp., °F
	73	64	RT

Specimen Details: Unnotched
0.200-inch net diameter (Ref. a)

Surface Condition:
Longitudinally polished to 4µ in. finish with no circumferential marks

Reference: 3.7.3.1.8(a)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Maximum Stress Equation:
Log N_f = 16.55-6.92 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.371
Standard Deviation, Log (Life) = 0.917
R^2 = 84%

Sample Size = 23

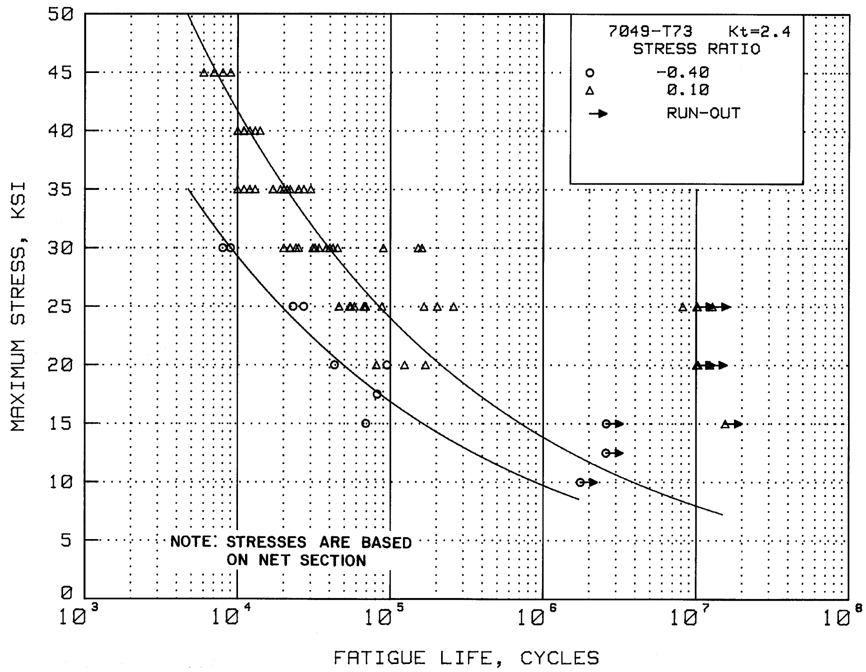


Figure 3.7.3.1.8(c). Best-fit S/N curves for notched, K_t = 2.4, 7049-T73 die forging, at room temperature, longitudinal, long-transverse and short-transverse directions.

Correlative Information for Figure 3.7.3.1.8(c)

Product Form: Die forging, 3 and 4.5-inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
(L)	77	68	RT Unnotched
	95	—	RT Notched
(LT)	73	64	RT Unnotched
	77	—	RT Notched
(ST)	75	66	RT Unnotched
	87	—	RT Notched

Specimen Details: Circumferentially notched, K_t = 2.4

(Ref. a)	(Ref. c)
0.150 or 0.200 inch net diameter	0.350-inch net diameter
	0.500-inch gross diameter
	0.032-inch notch root radius, r
	60° flank angle, ω

Surface Condition: Machined notch

References: 3.7.3.1.8(a) and (c)

Test Parameters:
Loading - Axial
Frequency - 1800 cpm
Temperature - RT
Environment - Lab air

No. of Heats/Lots: 2

Stress Life Equation:
Log N_f = 10.6-4.18 log (S_{eq})
$S_{eq} = S_{max} (1\text{-}R)^{0.80}$
Std. Error of Estimate, Log (Life) = 0.320
Standard Deviation, Log (Life) = 0.500
R^2 = 59%

Sample Size = 69

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

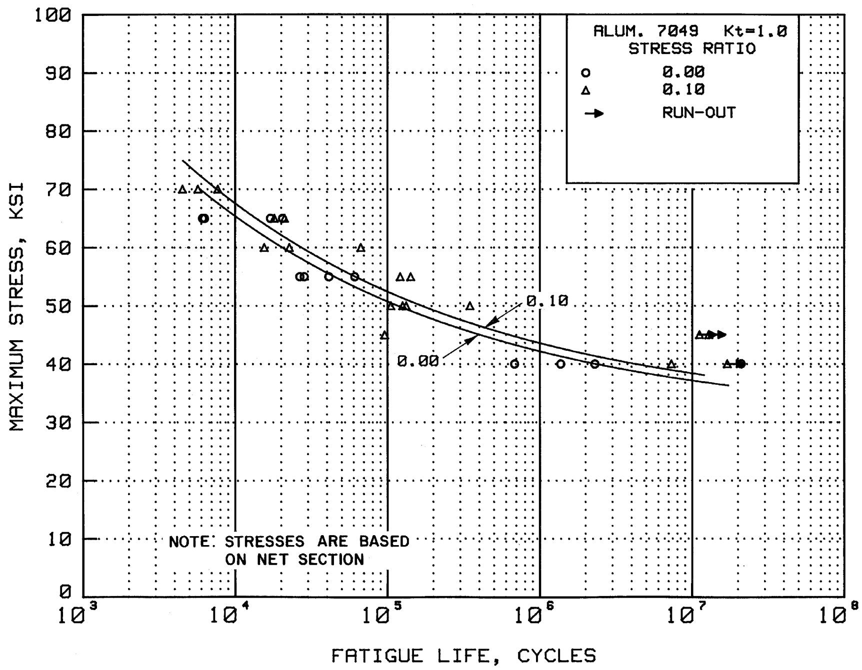


Figure 3.7.3.1.8(d). Best-fit S/N curves for unnotched 7049-T73 hand forging, longitudinal direction.

Correlative Information for Figure 3.7.3.1.8(d)

Product Form: Hand forging, 2.0 to 5.0-inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	70-80	60-73	RT

Specimen Details: Unnotched
0.125 and 0.300-inch diameter

Surface Condition:
Polished with increasingly finer grits of emery paper to surface roughness of 10 rms with polishing marks longitudinal, or not specified.

References: 3.2.6.1.9(d) and 3.7.3.1.8(e)

Test Parameters:
Loading - Axial
Frequency - 800, 1500, or 1725 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 6

Equivalent Stress Equation:
Log N_f = 10.6-4.31 log (S_{eq}-30)
$S_{eq} = S_{max}\ (1-R)^{0.31}$
Std. Error of Estimate, Log (Life) = 0.348
Standard Deviation, Log (Life) = 0.944
R^2 = 86%

Sample Size = 28

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

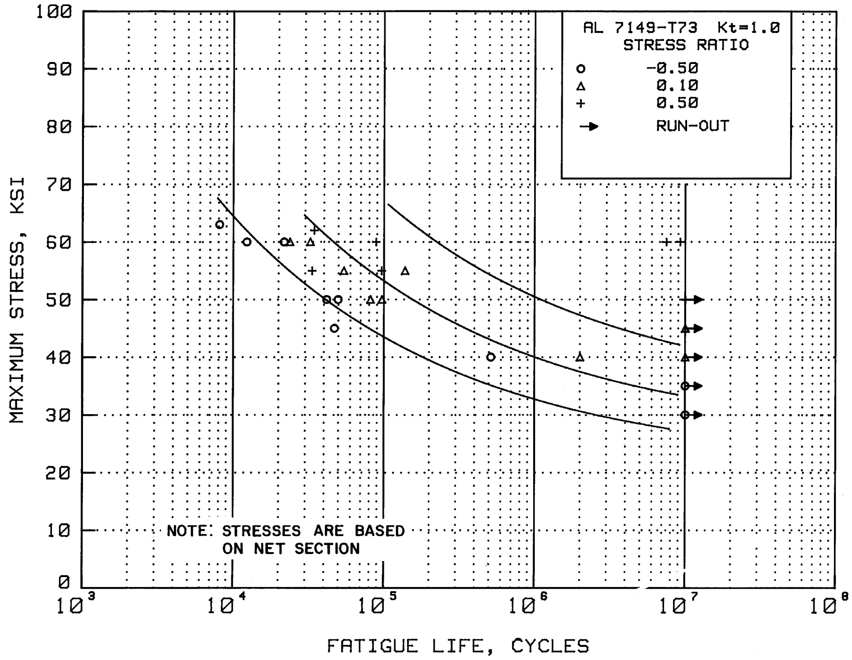


Figure 3.7.3.1.8(e). Best-fit S/N curves for unnotched 7149-T73 hand forging, long-transverse direction.

Correlative Information for Figure 3.7.3.1.8(e)

Product Form: Hand forging, 4.00 to 4.75-inches thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	73	64	RT

Specimen Details: Unnotched 0.250-inch diameter

Surface Condition: Not specified.

Reference: 3.7.3.1.8(e)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
Log N_f = 9.9-3.46 log (S_{eq}-25)
$S_{eq} = S_{max}$ $(1\text{-}R)^{0.39}$
Std. Error of Estimate, Log (Life) = 0.689
Standard Deviation, Log (Life) = 0.845
R^2 = 34%

Sample Size = 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

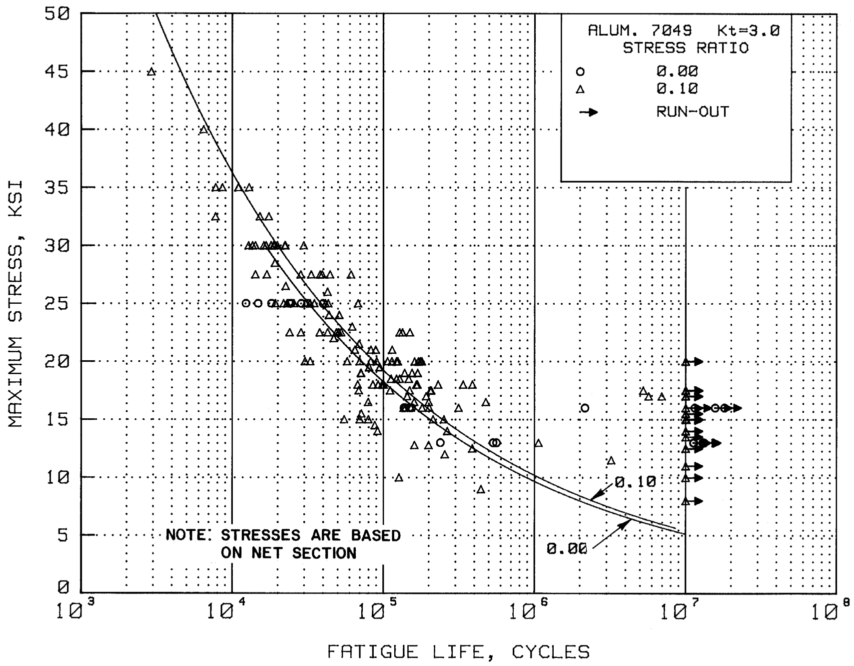


Figure 3.7.3.1.8(f). Best-fit S/N curves for notched, K_t = 3.0, 7049-T73 hand forging, longitudinal, long-transverse, and short-transverse directions.

Correlative Information for Figure 3.7.3.1.8(f)

Product Form: Hand forging, 2.0 to 5.0-inches thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	71-80	62-73	RT

Specimen Details: Circumferentially notched, K_t = 3.0
0.200, 0.300, and 0.306-inch gross diameter
0.175, 0.200, and 0.253-inch net diameter
0.006, 0.010, and 0.013-inch root radius, r
60° flank angle, ω

Surface Condition:
Polished with oil and alumdum grit applied to a rotating wire, or not specified.

References: 3.2.6.1.9(d), 3.7.3.1.8(d) and (e)

Test Parameters:
Loading - Axial
Frequency - 800, 1500, or 1725 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 8

Equivalent Stress Equation:
Log N_f = 9.57-3.63 log (S_{eq})
$S_{eq} = S_{max}\ (1\text{-}R)^{0.49}$
Std. Error of Estimate, Log (Life) = 0.344
Standard Deviation, Log (Life) = 0.562
R^2 = 63%

Sample Size = 151

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

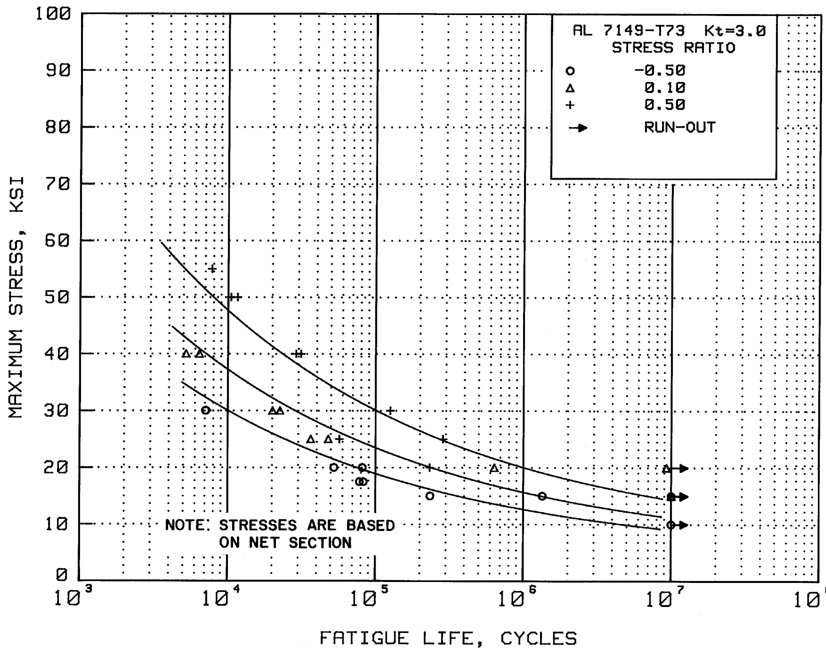


Figure 3.7.3.1.8(g). Best-fit S/N curves for notched, K_t = 3.0, 7149-T73 hand forging, long transverse direction.

Correlative Information for Figure 3.7.3.1.8(g)

Product Form: Hand forging, 4.00 to 4.75-inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	73	64	RT

Specimen Details: Circumferentially notched, K_t = 3.0
0.375-inch gross diameter
0.253-inch net diameter
0.013-inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

Reference: 3.7.3.1.8(e)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 3

Equivalent Stress Equation:
Log N_f = 10.1-4.10 log (S_{eq}-5)
$S_{eq} = S_{max} (1-R)^{0.42}$
Std. Error of Estimate, Log (Life) = 0.450
Standard Deviation, Log (Life) = 0.797
R^2 = 68%

Sample Size = 25

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

3.7.4 7050 ALLOY

3.7.4.0 *Comments and Properties* — 7050 is an Al-Zn-Mg-Cu-Zr alloy developed to have a combination of high strength, high resistance to stress-corrosion cracking, and good fracture toughness, particularly in thick sections. The use of zirconium in lieu of chromium provides a low sensitivity to quench, which results in high strengths in thick sections. Plate, hand, and die forgings in the T74 temper have static strengths about equivalent to those of corresponding products of 7079 in the T6 tempers and toughness levels equal to or higher than other conventional high-strength alloys.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Plate in the T7451 temper has stress-corrosion resistance higher than 7075-T7651, and hand and die forgings in the T7452 and T74 tempers, respectively, have stress-corrosion resistance similar to 7175-T74 forgings. The T73 temper provides the highest resistance to stress corrosion for this alloy. The T76 temper provides for good exfoliation resistance and higher stress-corrosion resistance than T6 tempers of 7075 and 7178. The T74 temper provides stress-corrosion and strength characteristics intermediate to those of T76 and T73. Refer to Section 3.1.2.3 for further comments regarding the resistance of the alloy to stress-corrosion cracking.

Refer to Section 3.1.3.4 for comments regarding the weldability of this alloy.

Material specifications for 7050 are shown in Table 3.7.4.0(a). Room-temperature properties are shown in Table 3.7.4.0(b_1) through (e_3).

Table 3.7.4.0(a). Material Specifications for 7050 Aluminum Alloy

Specification	Form
AMS 4050	Bare plate
AMS 4108	Hand forging
AMS 4107	Die forging
AMS 4333	Die forging
AMS 4340	Extruded shape
AMS 4341	Extruded shape
AMS 4342	Extruded shape
AMS 4201	Bare plate
MIL-A-22771	Forging

The temper index for 7050 is as follows:

Section	Temper
3.7.4.1	T73510 and T73511
3.7.4.2	T74, T7451, and T7452 (formerly T736, T73651, T73652)
3.7.4.3	T76510 and T76511

3.7.4.1 *T73510 and T73511 Tempers* — Figures 3.7.4.1.6(a) through (d) present stress-strain and tangent-modulus curves for extrusions. Fatigue data are presented in Figures 3.7.4.1.8(a) and (b).

3.7.4.2 *T74, T7451, and T7452 Tempers* — Elevated-temperature curves for T7451 plate are presented in Figure 3.7.4.2.1. Figures 3.7.4.2.6(a) through (j) present stress-strain and tangent-modulus curves for various products and tempers. Fatigue data are presented in Figures 3.7.4.2.8(a) through (l). Fatigue-crack-propagation data for T7451 plate are presented in Figures 3.7.4.2.9(a) through (c).

3.7.4.3 *T76510 and T76511 Tempers* — Figures 3.7.4.3.6(a) through (f) present stress-strain and tangent-modulus curves for extruded shapes. Fatigue data are presented in Figure 3.7.4.3.8(a) and (b).

Table 3.7.4.0(b_1). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Plate

Specification	AMS 4050															
Form	Plate															
Temper	T7451															
Thickness, in.	0.250-1.500		1.501-2.000		2.001-3.000		3.001-4.000		4.001-5.000		5.001-6.000		6.001 - 7.000		7.001 - 8.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																
F_{tu}, ksi:																
L	74[a]	76	74	76	73[a]	75	72	74	71[a]	73	70[a]	72	69	72	68	71
LT	74	76	74[a]	76	73[a]	75	72	75	71[a]	74	70	73	69	72	68	71
ST	...	...	...	...	68	72	68[a]	71	67	70	66	69	66	68	65	67
F_{ty}, ksi:																
L	64[a]	67	64[a]	66	63[a]	66	62[a]	65	61[a]	65	60	63	59	62	59	63
LT	64	66	64	66	63[a]	66	62	65	61	64	60	62	59	62	58	61
ST	...	...	...	...	59	61	57	60	57[a]	60	57	59	56	58	56	58
F_{cy}, ksi:																
L	63	64	62	64	61	64	60	63	58	61	57	59	56	59	55	57
LT	66	68	67	69	66	69	65	68	64	67	63	66	60	63	59	62
ST	...	...	...	...	63	66	63	66	63	66	62	64	60	63	59	62
F_{su}, ksi	42	43	43	44	43	44	43	45	43	45	43	45	44	46	44	46
F_{bru}[b], ksi:																
(e/D = 1.5)	107	110	109	112	108	111	107	111	107	111	105	110	107	112	103	108
(e/D = 2.0)	140	144	142	146	141	144	140	144	138	144	137	142	136	143	132	138
F_{bry}[b], ksi:																
(e/D = 1.5)	86	89	89	92	89	93	90	94	90	95	91	94	84	89	83	87
(e/D = 2.0)	101	104	104	107	104	109	104	109	105	110	105	108	99	105	98	102
e, percent (S-basis):																
L	10	...	10	...	9	...	9	...	9	...	8	...	7	...	6	...
LT	9	...	9	...	8	...	6	...	5	...	4	...	4	...	4	...
ST	...	...	...	...	3	...	3	...	3	...	3	...	3	...	3	...
E, 10^3 ksi	10.3															
E_c, 10^3 ksi	10.6															
G, 10^3 ksi	3.9															
μ	0.33															
Physical Properties:																
ω, lb/in.^{3}	0.102															
C, Btu/(lb)(°F)	0.23 (at 212°F)															
K, Btu/[(hr)(ft^2)(°F)/ft]	91 (at 77°F)															
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)															

a S-basis values. See Table 3.7.4.0(b_2) for rounded T_{99} values.

b See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.4.0(b_2). Rounded T_{99} Values for Tensile Yield and Ultimate Strength for 7050-T7451 Plate

Thickness, in.	0.250-1.500	1.501-2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Mechanical Properties:						
F_{tu}, ksi:						
L	75	...	74	...	72	71
LT	...	75	74	...	72	...
ST	...	...	...	69	...	...
F_{ty}, ksi:						
L	65	65	65	63	62	...
LT	...	...	64	...	...	...
ST	...	...	...	...	58	...

Table 3.7.4.0(b_3). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Plate

Specification	AMS 4201							
Form	Plate							
Temper	T7651							
Thickness, in.	0.250-1.000	1.001-1.500		1.501-2.000		2.001-2.500		2.501-3.000
Basis	S	A	B	A	B	A	B	S
Mechanical Properties:								
F_{tu}, ksi:								
L	76	77[a]	...	76	78	75	78	76
LT	76	76	79	75	78	75	78	76
ST	...	...	...	72	75	70	73	70
F_{ty}, ksi:								
L	66	67[a]	...	66	70	66	70	66
LT	66	66	70	65	69	65	69	66
ST	...	...	...	59	63	60	62	60
F_{cy}, ksi:								
L	64	64	68	64	67	64	67	64
LT	68	68	73	68	72	68	72	69
ST	...	...	...	67	71	67	71	68
F_{su}, ksi	43	44	46	44	46	45	47	46
F_{bru}[b], ksi:								
(e/D = 1.5)	110	112	117	112	117	114	118	116
(e/D = 2.0)	142	144	150	144	150	146	151	149
F_{bry}[b], ksi:								
(e/D = 1.5)	87	90	96	91	96	93	98	96
(e/D = 2.0)	102	105	111	105	112	107	114	110
e, percent (S-basis):								
L	9	9	...	9	...	8	...	8
LT	8	8	...	8	...	7	...	7
ST	...	...	...	...	...	1.5	...	1.5
E, 10^3 ksi	10.3							
E_c, 10^3 ksi	10.8							
G, 10^3 ksi	4.0							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.102							
C, Btu/(lb)(°F)	0.23 (at 212°F)							
K, Btu/[(hr)(ft^2)(°F)/ft]	89 (at 77°F)							
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)							

a S-basis values since T_{99} values could not be determined.

b See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.4.0(c_1). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Die Forging

Specification	AMS 4107 and AMS-A-22771			
Form	Die forging			
Temper	T74[a]			
Thickness[b], in.	≤2.000	2.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	72	71	70	70
T[c]	68	67	66	66
F_{ty}, ksi:				
L	62	61	60	59
T[c]	56	55	54	54
F_{cy}, ksi:				
L	63	63	63	62
ST	60	59	58	57
F_{su}, ksi	42	42	41	41
F_{bru}[d], ksi:				
(e/D = 1.5)	99	98	97	97
(e/D = 2.0)	131	129	127	127
F_{bry}[d], ksi:				
(e/D = 1.5)	82	81	78	78
(e/D = 2.0)	96	95	92	92
e, percent:				
L	7	7	7	7
T[c]	5	4	3	3
E, 10^3 ksi	10.2			
E_c, 10^3 ksi	10.7			
G, 10^3 ksi	3.9			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.102			
C, Btu/(lb)(°F)	0.23 (at 212°F)			
K, Btu/[(hr)(ft^2)(°F)/ft]	91 (at 77°F)			
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)			

a Design values were based upon data obtained from testing T74 die forgings, heat treated by suppliers and supplied in T74 temper.

b Thickness at the time of heat treatment. When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.

c T indicates any grain direction not within ±15° of being parallel to the forging flow lines. F_{cy}(T) values are based upon short transverse (ST) test data.

d Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.4.0(c_2). Design Mechanical and Physical Properties of 7050-T7452 Aluminum Alloy Die Forging

Specification	AMS 4333			
Form	Die forgings			
Temper	T7452			
Thickness[b], in.	≤2.000		2.001-4.000	
Basis	A	B	A	B
Mechanical Properties:				
F_{tu}, ksi:				
L	71	73	71	72
T[a]	68[b]	73	67[c]	71
F_{ty}, ksi:				
L	60	63	59	61
T[a]	55[b]	61	53[c]	61
F_{cy}, ksi:				
L	63	66	62	64
ST	63	66	62	64
F_{su}, ksi	43	44	43	43
F_{bru}[d], ksi:				
(e/D = 1.5)	101	104	101	103
(e/D = 2.0)	135	139	135	137
F_{bry}[d], ksi:				
(e/D = 1.5)	87	92	86	89
(e/D = 2.0)	105	110	103	106
e, percent (S-basis):				
L	8		8	
T[a]	5		4	
E, 10^3 ksi	10.2			
E_c, 10^3 ksi	10.5			
G, 10^3 ksi	3.9			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.102			
C, Btu/(lb)(°F)	0.23 (at 212°F)			
K, Btu/[(hr)(ft^2)(°F)/ft]	91 (at 77°F)			
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)			

a T indicates any grain direction not within ±15° of being perpendicular to the forging flow lines. F_{cy}(T) values are based on short transverse (ST) test data.
b S-basis. The T_{99} values are higher than the specification minimum values as follows: F_{tu}(T)=70.10 ksi, F_{ty}(t)=57.50 ksi.
c S-basis. The T_{99} values are higher than the specification minimum values as follows: F_{tu}(T)=69.36 ksi, F_{ty}(t)=57.38 ksi.
d Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.4.0(d). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Hand Forging

Specification	AMS 4108 and AMS-A-22771							
Form	Hand Forging							
Temper	T7452							
Thickness, in.	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	6.001-7.000		7.001-8.000
Basis	S	S	S	S	S	A	B	S
Mechanical Properties:								
F_{tu}, ksi:								
L	72	72	71	70	69	68	71	67
LT	71	70	70	69	68	67	70	66
ST	...	67	67	66	66	65	69	64
F_{ty}, ksi:								
L	63	62	61	60	59	56	61	57
LT	61	60	59	58	56	54[a]	59	52
ST	...	55	55	54	53	51[a]	56	50
F_{cy}, ksi:								
L	63	62	61	60	58	56	61	54
LT	64	63	62	61	59	57	62	55
ST	...	63	61	60	58	56	61	54
F_{su}, ksi	42	41	41	41	40	40	41	39
F_{bru}[b], ksi:								
(e/D = 1.5)	98	97	97	96	94	93	97	91
(e/D = 2.0)	131	129	129	127	125	123	129	121
F_{bry}[b], ksi:								
(e/D = 1.5)	86	84	83	82	79	76	83	73
(e/D = 2.0)	101	100	98	96	93	90	98	86
e, percent (S-basis):								
L	9	9	9	9	9	9	...	9
LT	5	5	5	4	4	4	...	4
ST	...	4	4	3	3	3	...	3
E, 10^3 ksi	10.2							
E_c, 10^3 ksi	10.6							
G, 10^3 ksi	3.9							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.102							
C, Btu/(lb)(°F)	0.23 (at 212°F)							
K, Btu/[(hr)(ft^2)(°F)/ft]	91 (at 77°F)							
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)							

a S-basis values. The rounded T_{99} values for F_{ty}(LT) = 56 ksi and F_{ty}(ST) = 52 ksi.

b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.4.0(e_1). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Extrusion

Specification	AMS 4341				
Form	Extrusion				
Temper	T73511				
Cross-Sectional Area, in^2	≤32				
Thickness or Diameter,[a] in.	≤1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	70	70	70	70	70
LT	68	66	65	63	62
F_{ty}, ksi:					
L	60	60	60	60	60
LT	57	56	55	53	52
F_{cy}, ksi:					
L	60	60	60	61	61
LT	60	59	58	56	55
F_{su}, ksi	39	39	38	37	36
F_{bru}[b], ksi:					
(e/D = 1.5)	103	100	96	91	87
(e/D = 2.0)	133	129	124	120	115
F_{bry}[b], ksi:					
(e/D = 1.5)	82	80	78	76	74
(e/D = 2.0)	97	95	93	91	88
e, percent:					
L	8	8	8	8	8
E, 10^3 ksi	10.3				
E_c, 10^3 ksi	10.7				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.102				
C, Btu/(lb)(°F)	0.23 (at 212°F)				
K, Btu/[(hr)(ft^2)(°F)/ft]	93 (at 77°F)				
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)				

a The mechanical properties are to be based upon the thickness at the time of quench.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.4.0(e_2). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Extrusion

Specification	AMS 4342				
Form	Extrusion[a]				
Temper	T74511				
Cross-Sectional Area, in^2	≤32				
Thickness or Diameter,[b] in.	≤1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	73	73	73	73	73
LT	71	69	68	64	64
F_{ty}, ksi:					
L	63	63	63	63	63
LT	60	59	58	56	54
F_{cy}, ksi:					
L	63	63	63	64	64
LT	63	62	61	59	57
F_{su}, ksi	41	40	40	39	38
F_{bru}[c], ksi:					
(e/D = 1.5)	107	104	100	95	91
(e/D = 2.0)	139	135	130	125	121
F_{bry}[c], ksi:					
(e/D = 1.5)	86	84	82	80	78
(e/D = 2.0)	106	100	98	95	92
e, percent:					
L	7	7	7	7	7
E, 10^3 ksi	10.3				
E_c, 10^3 ksi	10.7				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.102				
C, Btu/(lb)(°F)	0.23 (at 212°F)				
K, Btu/[(hr)(ft^2)(°F)/ft]	93 (at 77°F)				
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)				

a Excluding tubing.
b The mechanical properties are to be based upon the thickness at the time of quench.
c Bearing values are “dry pin” values per Section 1.4.7.1.

Table 3.7.4.0(e_3). Design Mechanical and Physical Properties of 7050 Aluminum Alloy Extrusion

Specification	AMS 4340						
Form	Extrusion						
Temper	T76511						
Thickness,[a] in.	≤0.499		0.500-1.000	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000
Basis	A	B	S	S	S	S	S
Mechanical Properties:							
F_{tu}, ksi:							
L	77	79	79	79	79	79	79
LT	76	78	77	75	73	71	68
F_{ty}, ksi:							
L	68	71	69	69	69	69	69
LT	67	69	67	65	63	61	59
F_{cy}, ksi:							
L	68	71	69	69	69	69	69
LT	70	73	70	69	67	66	64
F_{su}, ksi	42	44	43	43	42	41	40
F_{bru}[b], ksi:							
(e/D = 1.5)	113	116	115	114	110	107	103
(e/D = 2.0)	147	151	150	148	144	140	136
F_{bry}[b], ksi:							
(e/D = 1.5)	94	98	94	92	89	86	82
(e/D = 2.0)	109	114	110	108	104	98	93
e, percent (S-basis):							
L	7	...	7	7	7	7	7
E, 10^3 ksi	10.3						
E_c, 10^3 ksi	10.7						
G, 10^3 ksi	3.9						
μ	0.33						
Physical Properties:							
ω, lb/in.^{3}	0.102						
C, Btu/(lb)(°F)	0.23 (at 212°F)						
K, Btu/[(hr)(ft^2)(°F)/ft]	89 (at 77°F)						
α, 10^{-6} in./in./°F	12.8 (68 to 212°F)						

a The mechanical properties are to be based upon the thickness at the time of quench.

b Bearing values are "dry pin" values per Section 1.4.7.1.

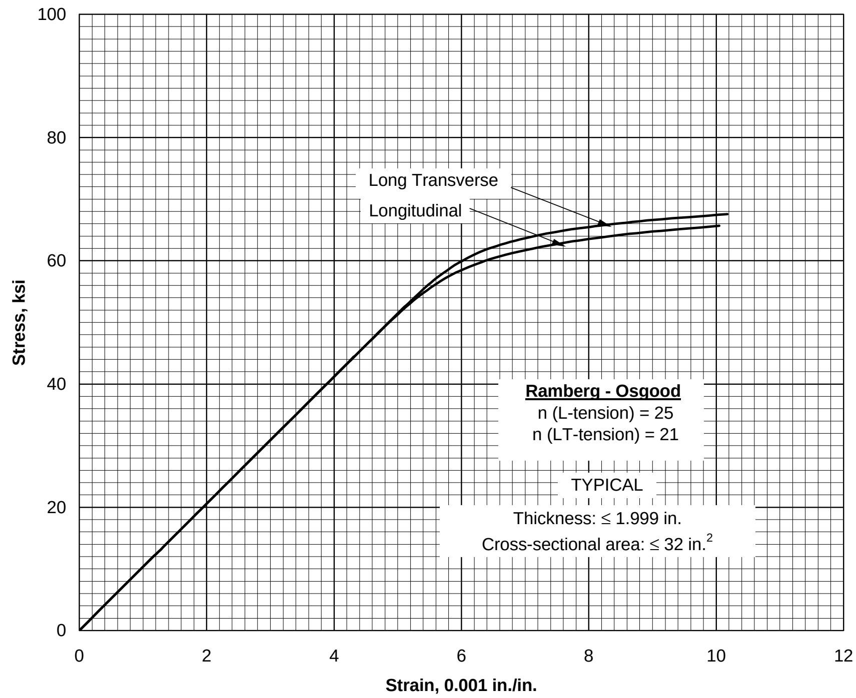


Figure 3.7.4.1.6(a). Typical tensile stress-strain curves for 7050-T7351X aluminum alloy extrusion at room temperature.

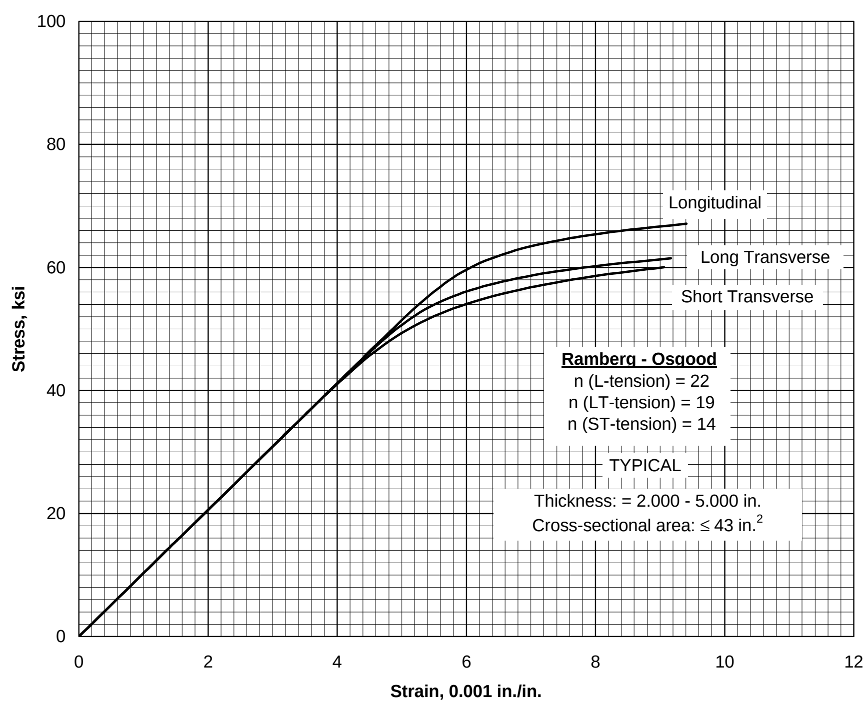


Figure 3.7.4.1.6(b). Typical tensile stress-strain curves for 7050-T7351X aluminum alloy extrusion at room temperature.

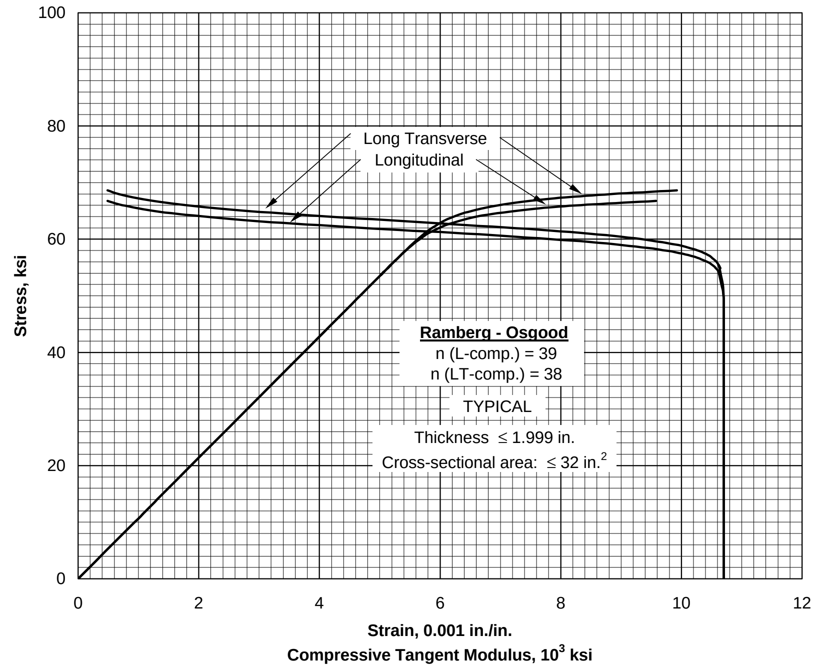


Figure 3.7.4.1.6(c). Typical compressive stress-strain and tangent-modulus curves for 7050-T7351X aluminum alloy extrusion at room temperature.

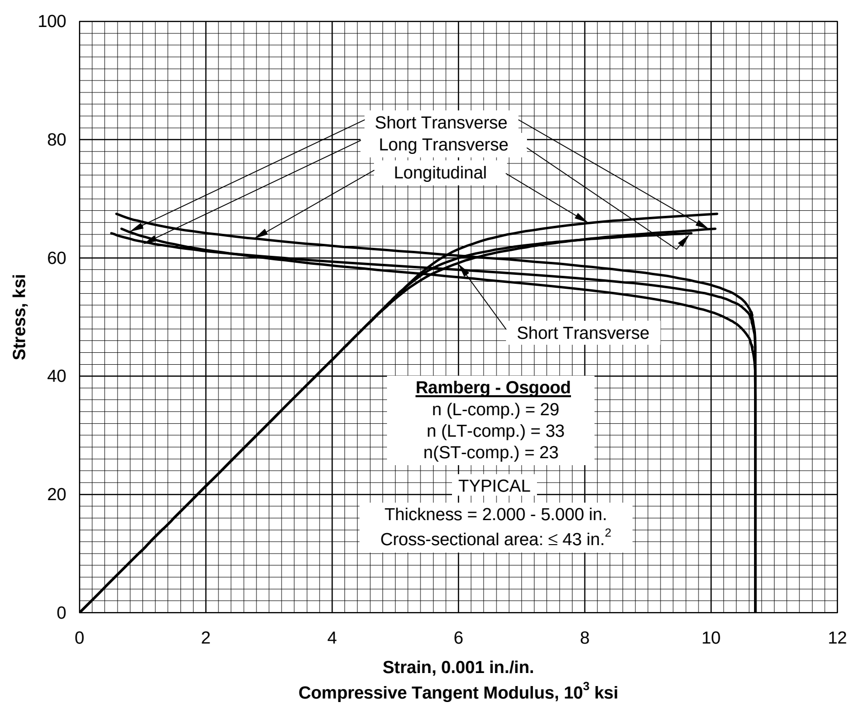


Figure 3.7.4.1.6(d). Typical compressive stress-strain and tangent-modulus curves for 7050-T7351X aluminum alloy extrusion at room temperature.

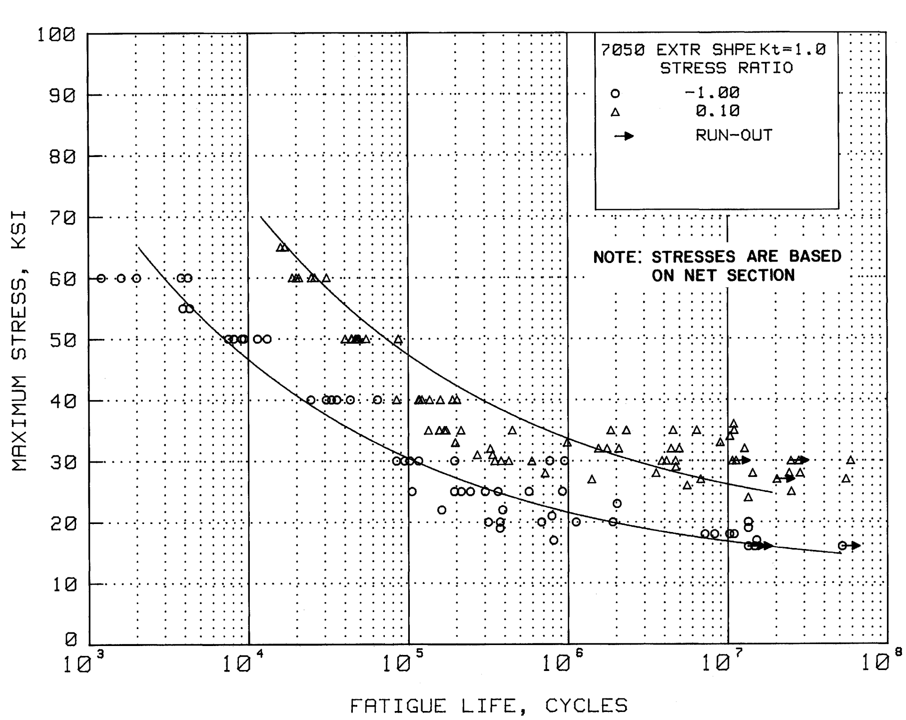


Figure 3.7.4.1.8(a). Best-fit S/N curves for unnotched 7050-T7351X extruded shape, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.4.1.8(a)

Product Form: Extruded shape, 0.5 to 5.0-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	72-79	62-69	RT

Specimen Details: Unnotched

0.300-inch diameter

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 10.5-3.79 log (S_{eq}-16)
$S_{eq} = S_{max}\ (1\text{-}R)^{0.55}$
Std. Error of Estimate, Log (Life) = 0.516
Standard Deviation, Log (Life) = 1.10
R^2 = 78%

Sample Size = 128

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

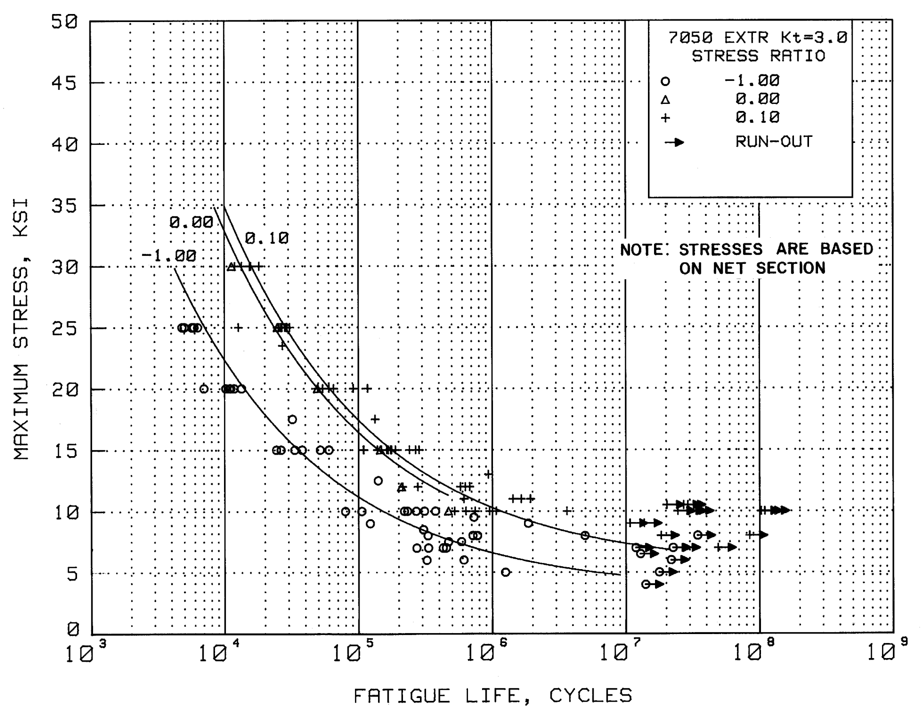


Figure 3.7.4.1.8(b). Best-fit S/N curves for notched, K_t = 3.0, 7050-T7351X extruded shape, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.4.1.8(b)

Product Form: Extruded shape, 0.5 to 5.0 inch thick

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
72-79	62-69	RT

Specimen Details: Circumferentially notched, K_t = 3.0
0.359-inch gross diameter
0.253-inch net diameter
0.013-inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 7.73\text{-}2.58 \log (S_{eq}\text{-}5.0)$
$S_{eq} = S_{max} (1\text{-}R)^{0.56}$
Std. Error of Estimate, Log (Life) = 0.268
Standard Deviation, Log (Life) = 0.733
R^2 = 87%

Sample Size = 103

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

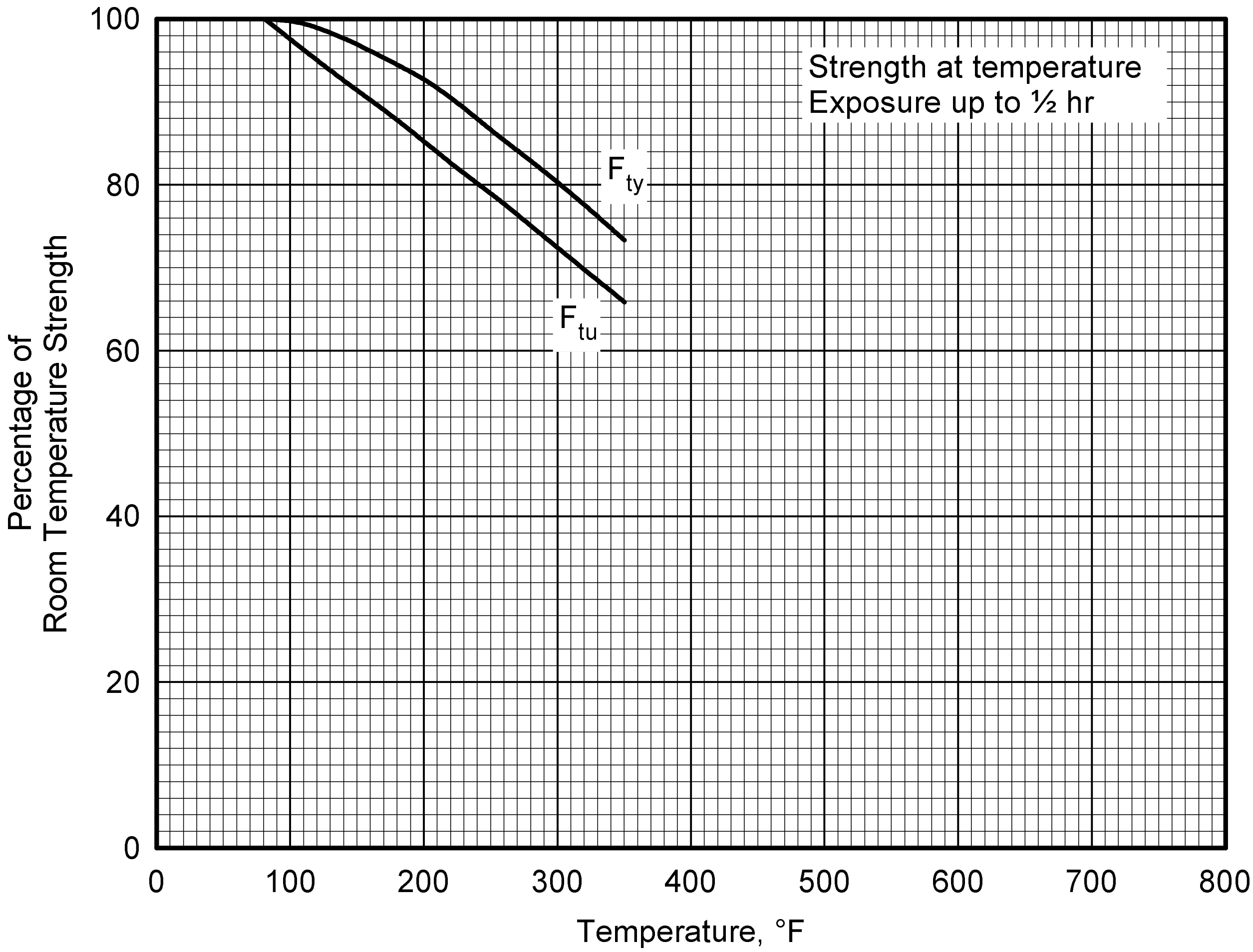


Figure 3.7.4.2.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of 7050-T7451 aluminum alloy plate.

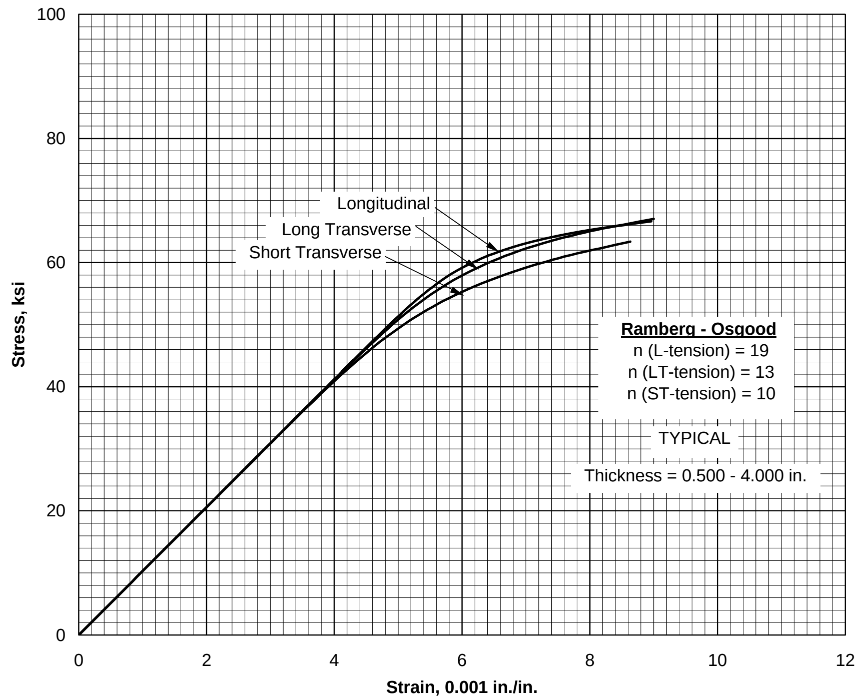


Figure 3.7.4.2.6(a). Typical tensile stress-strain curves for 7050-T7451 aluminum alloy plate at room temperature.

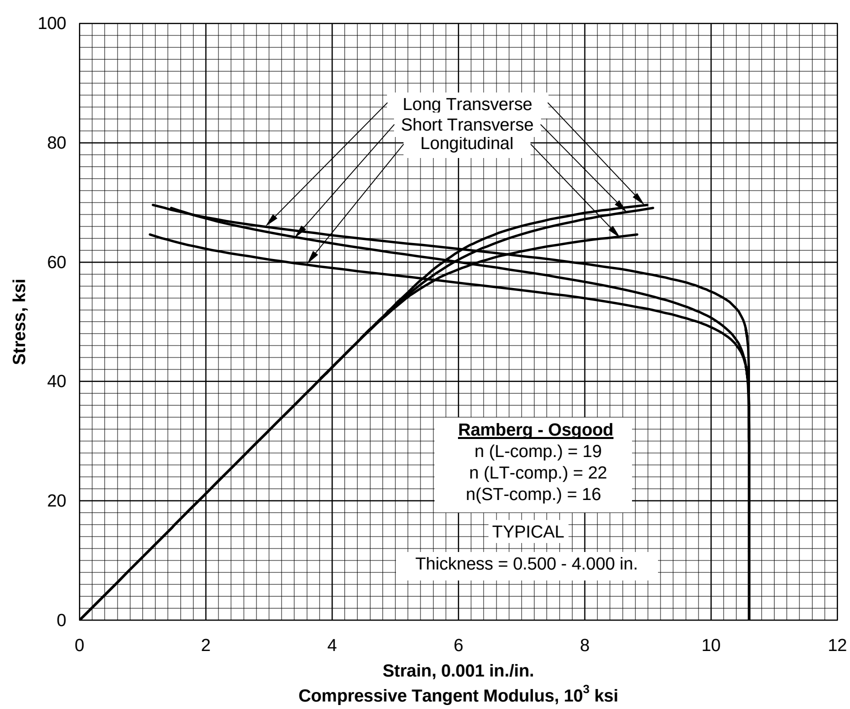


Figure 3.7.4.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7451 aluminum alloy plate at room temperature.

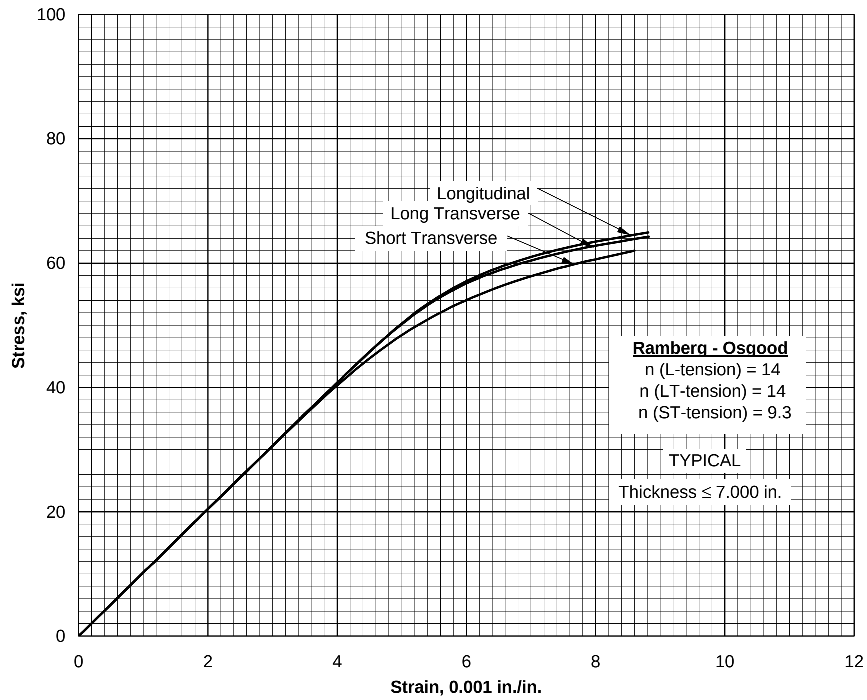


Figure 3.7.4.2.6(c). Typical tensile stress-strain curves for 7050-T7452 aluminum alloy hand forging at room temperature.

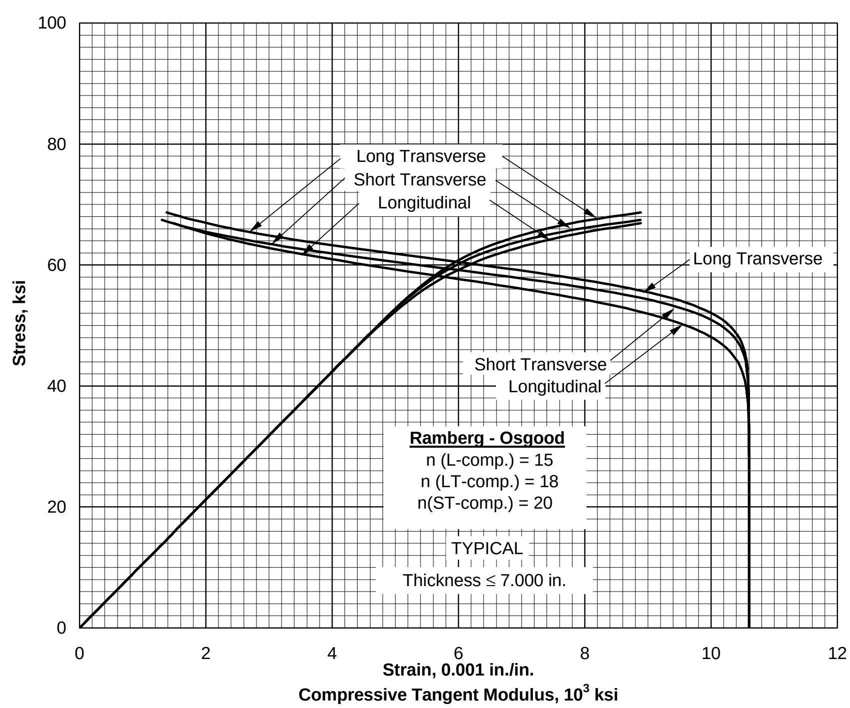


Figure 3.7.4.2.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7452 aluminum alloy hand forging at room temperature.

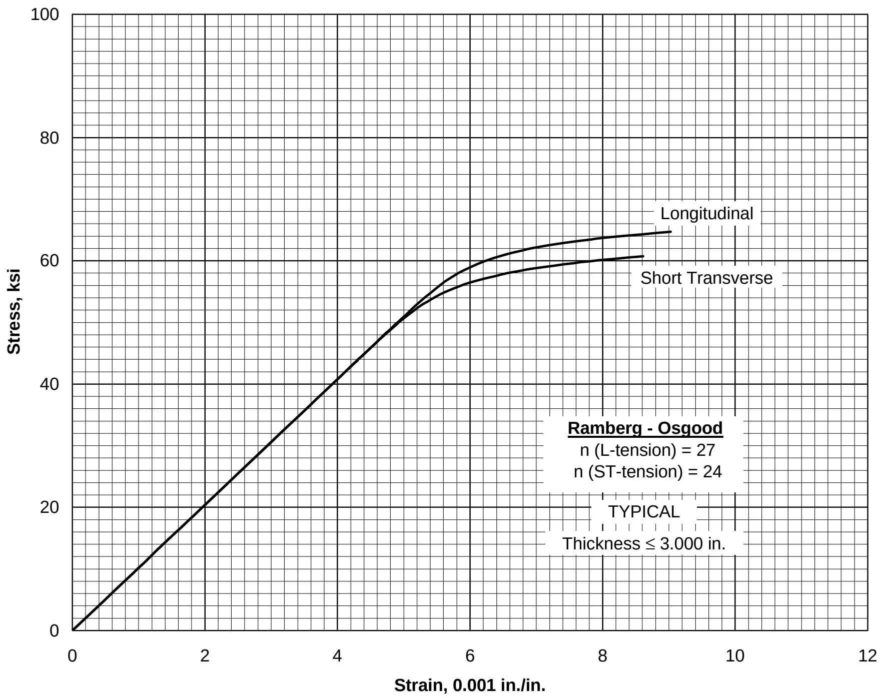


Figure 3.7.4.2.6(e). Typical tensile stress-strain curves for 7050-T74 aluminum alloy die forging at room temperature.

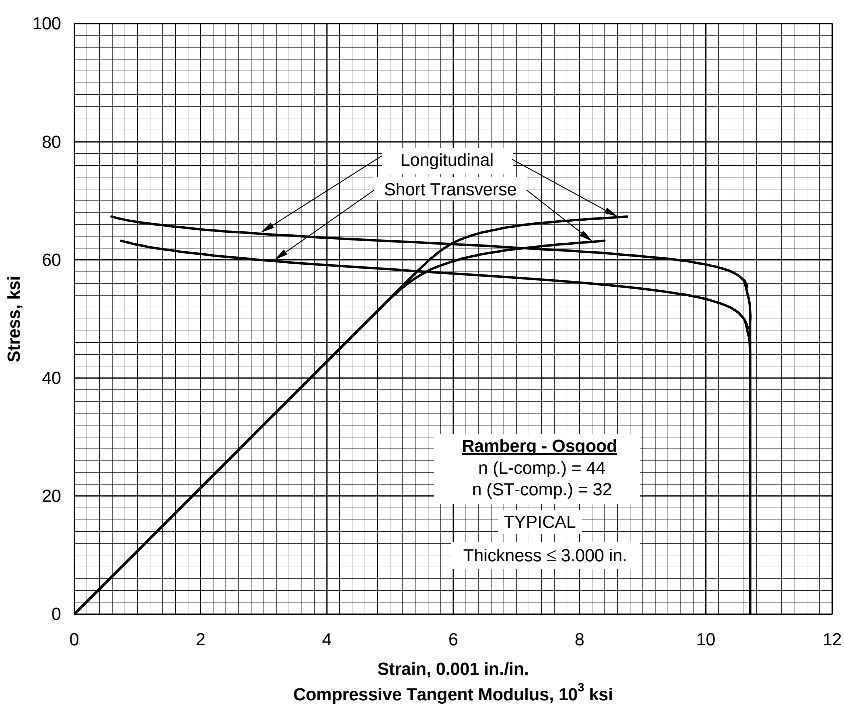


Figure 3.7.4.2.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T74 aluminum alloy die forging at room temperature.

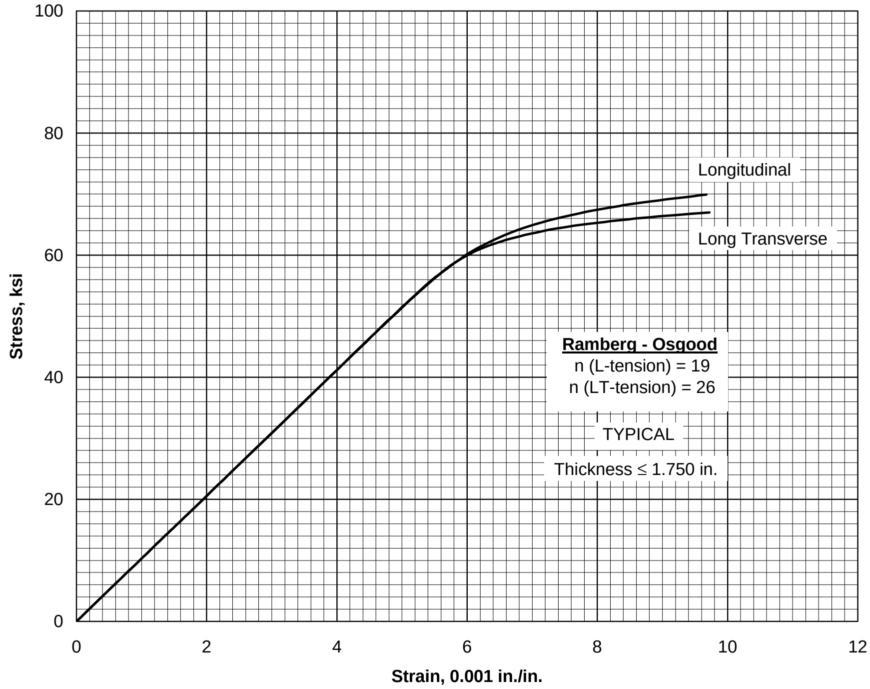


Figure 3.7.4.2.6(g). Typical tensile stress-strain curves for 7050-T74511 aluminum alloy extrusion at room temperature.

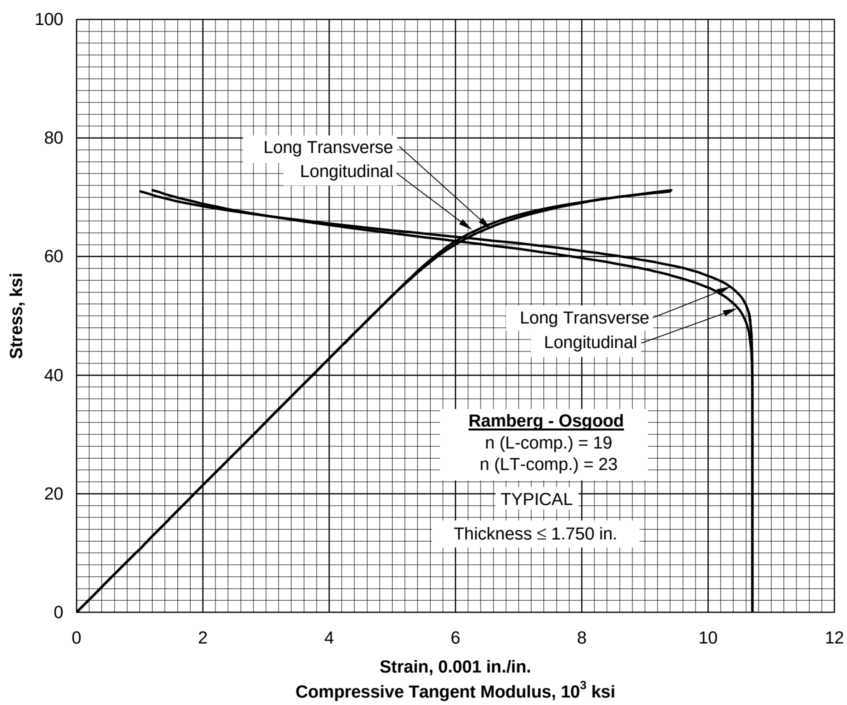


Figure 3.7.4.2.6(h). Typical compressive stress-strain and tangent-modulus curves for 7050-T74511 aluminum alloy extrusion at room temperature.

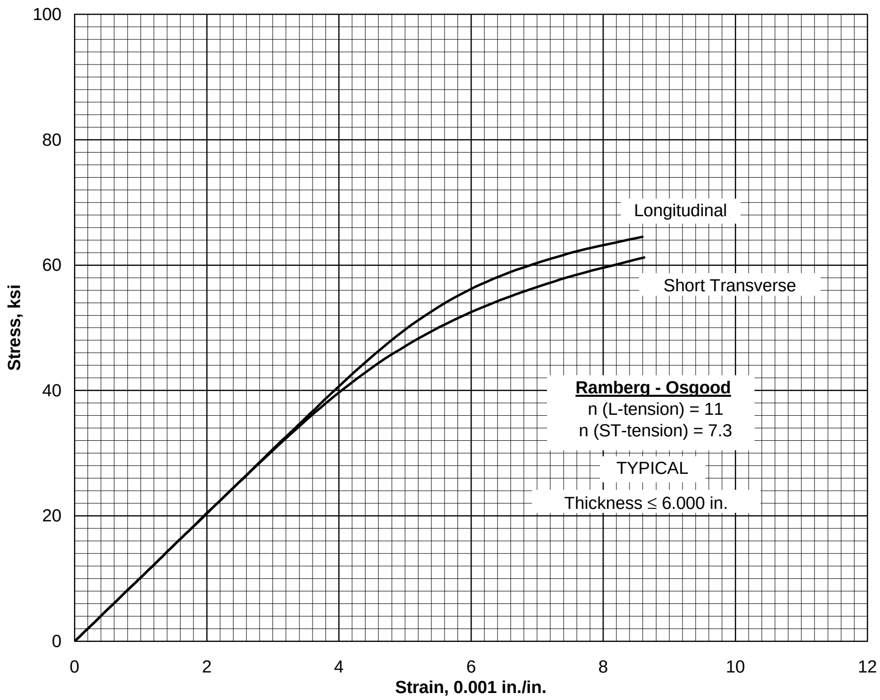


Figure 3.7.4.2.6(i). Typical tensile stress-strain curves for 7050-T7452 aluminum alloy die forging at room temperature.

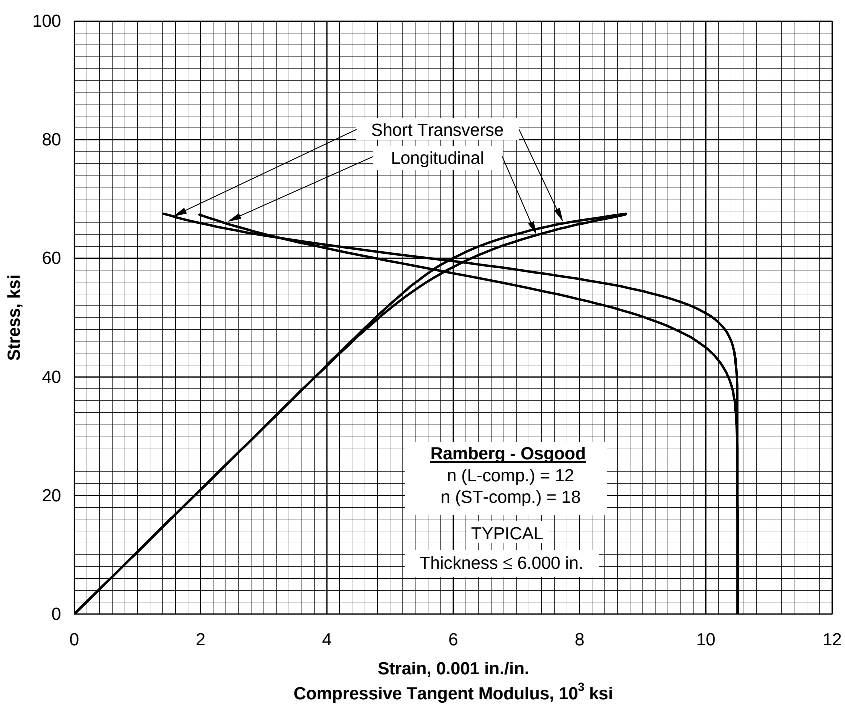


Figure 3.7.4.2.6(j). Typical compressive stress-strain and tangent-modulus curves for 7050-T7452 aluminum alloy die forging at room temperature.

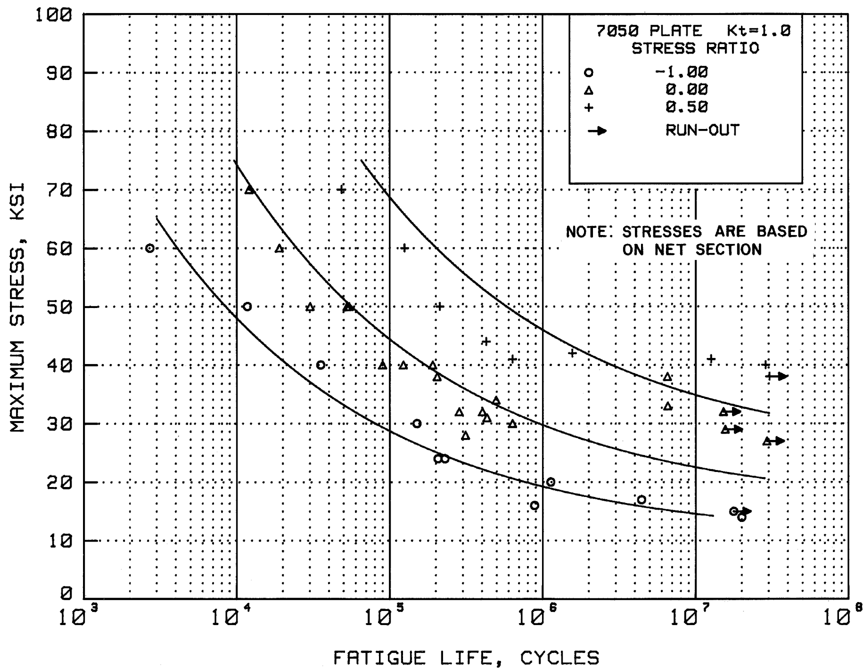


Figure 3.7.4.2.8(a). Best-fit S/N curves for unnotched 7050-T7451 plate, longitudinal direction and T/2 specimen location.

Correlative Information for Figure 3.7.4.2.8(a)

Product Form: Plate, 1.0-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	79	72	RT

Specimen Details: Unnotched
0.300-inch diameter

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.8.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
$\text{Log } N_f = 9.73\text{-}3.24 \log (S_{eq}\text{-}15.5)$
$S_{eq} = S_{max} (1\text{-}R)^{0.63}$
Std. Error of Estimate, Log (Life) = 0.490
Standard Deviation, Log (Life) = 0.942
R^2 = 73%

Sample Size = 35

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

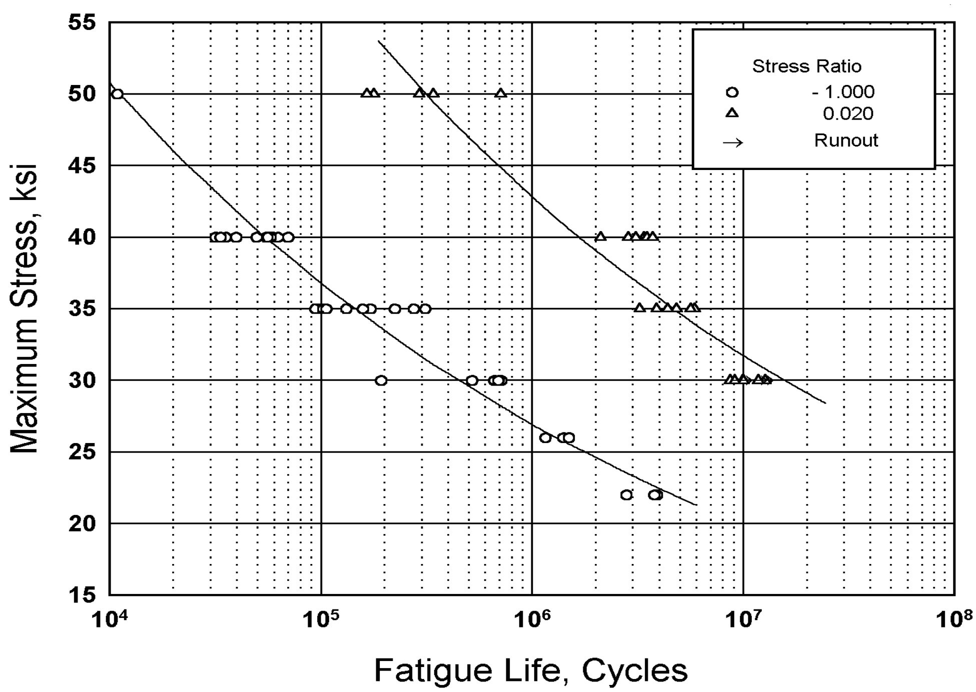


Figure 3.7.4.2.8(b). Best-fit S/N curves for unnotched 7050-T7451 plate, long transverse direction, t/4 specimen location.

Correlative Information for Figure 3.7.4.2.8(b)

Product Form: Plate, 4.25 to 8.50 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	N/A	62-67	RT

Specimen Details: Unnotched
0.250-inch diameter

Surface Condition: Polished, final surface finish unspecified

References: 3.7.4.2.8(d) and (e)

Test Parameters:
Loading – Axial
Frequency – 20 Hz
Temperature – RT
Environment – Air

Equivalent Stress Equation:
$\text{Log}(N_f) = 16.410 - 6.624 \log(S_{eq} - 5.0)$
$S_{eq} = S_{max}(1 - R)^{0.65}$
Std. Error of Estimate, Log (Life) = 0.183
Standard Deviation, Log (Life) = 0.814
$R^2 = 95.0\%$

Sample Size = 57

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

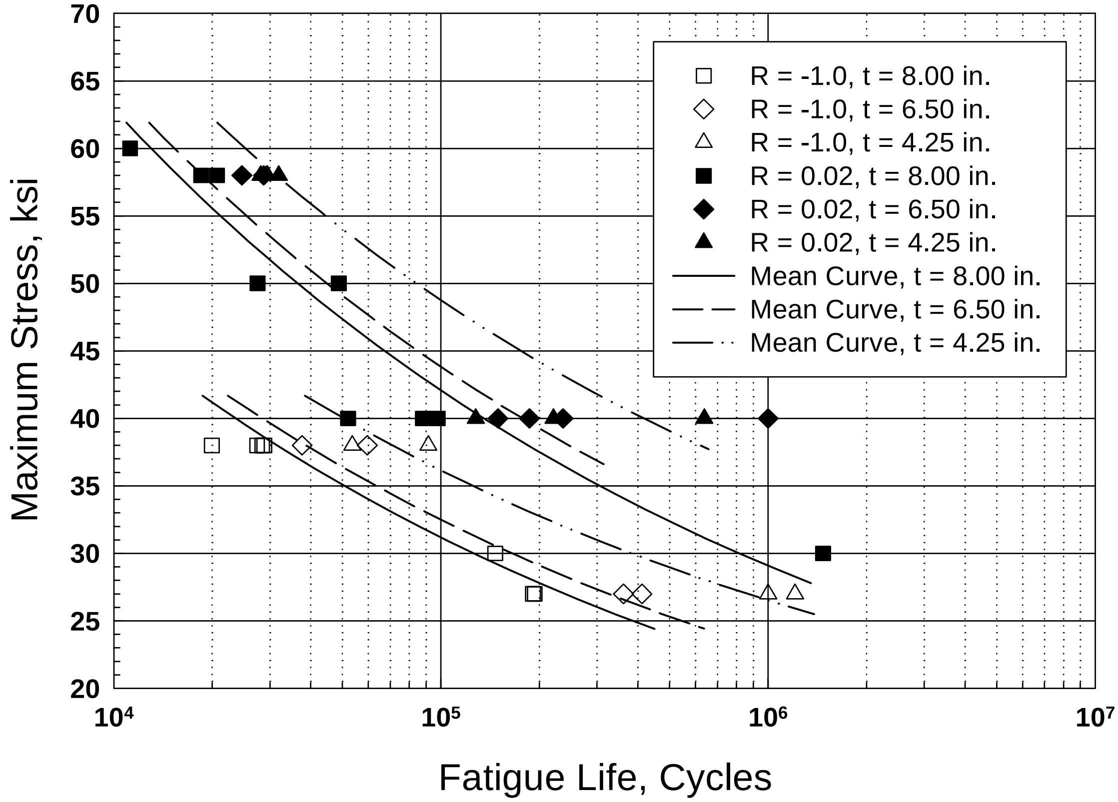


Figure 3.7.4.2.8(c). Best-fit S/N curves for unnotched 7050-T7451 plate, long transverse direction, t/2 specimen location.

Correlative Information for Figure 3.7.4.2.8(c)

Product Form: Plate, 4.25 to 8.50 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	N/A	62-67	RT

Specimen Details: Unnotched
0.250-inch diameter

Surface Condition: Polished, final surface finish unspecified

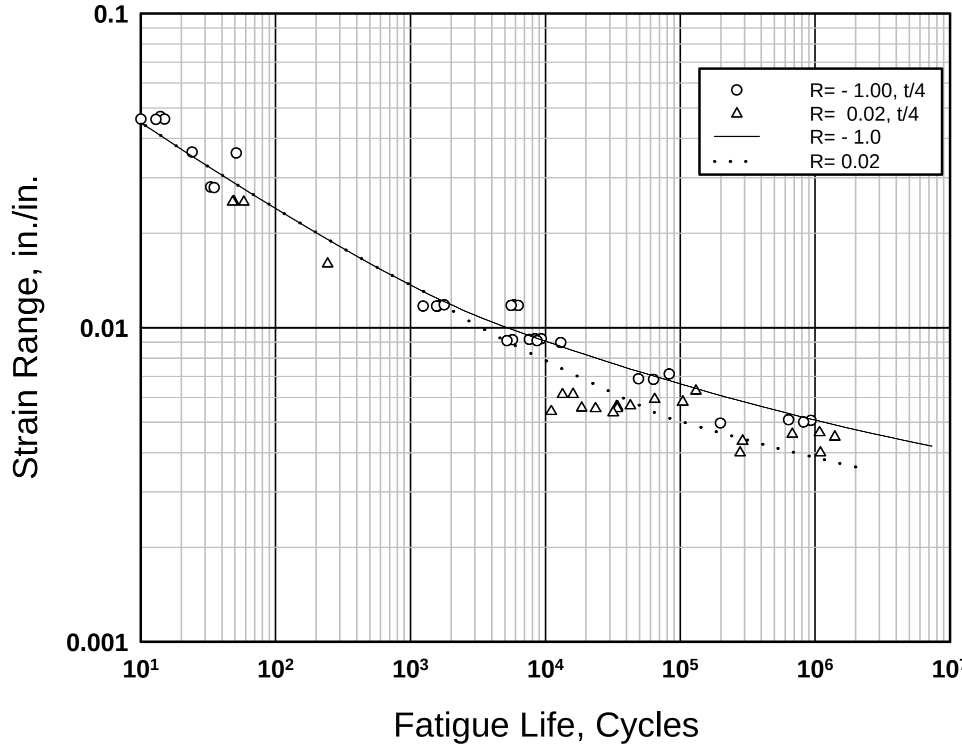
References: 3.7.3.2.8(d) and (e)

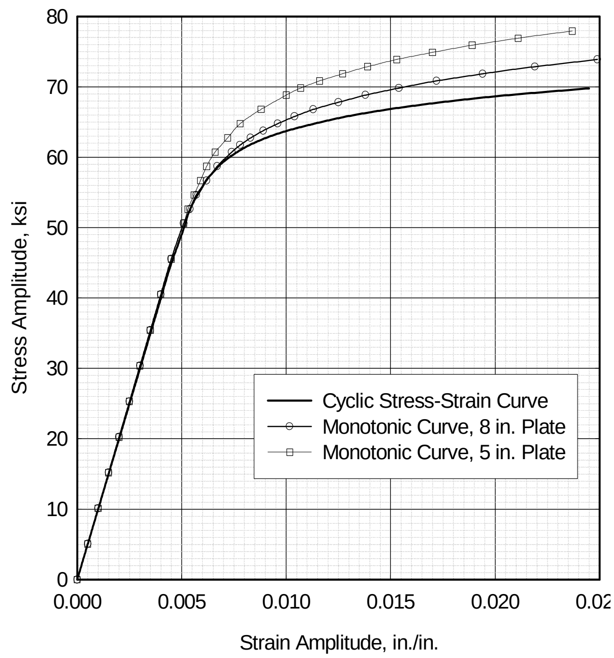
Test Parameters:
Loading – Axial
Frequency – 20 Hz
Temperature – RT
Environment – Air

Equivalent Stress Equation:
$\text{Log}(N_f) = 12.484 - 4.878 \log(S_{eq} - 60 / t)$
$S_{eq} = S_{max}(1 - R)^{0.42}$
t = plate thickness in inches.
Std. Error of Estimate, Log (Life) = 0.204
Standard Deviation, Log (Life) = 0.594
R^2 = 88.2%

Sample Size = 36

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios and plate thicknesses beyond those represented above.]





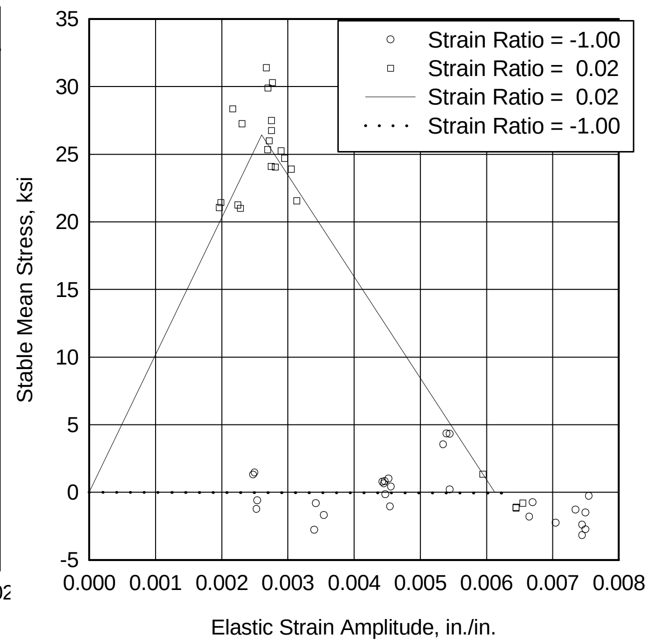


Figure 3.7.4.2.8(d). Best-fit strain-life curves, cyclic stress-strain curve, and mean stress relaxation curve for 7050-T7451 plate, long transverse direction, t/4 specimen location.

Correlative Information for Figure 3.7.4.2.8(d)

Product Form: Plate, 4.25 to 8.50 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., F
	N/A	62-67	RT

Stress-Strain Equations:
Cyclic Stress Strain Curve
$(\Delta\sigma/2) = 88.185\ (\Delta\epsilon_p/2)^{0.0578}$
Mean Stress Relaxation Curve
Minimal relaxation
for $(\Delta\epsilon/2) < 0.00261$
$\sigma_m = 46.0 - 7500\ (\Delta\epsilon/2)$
for $(\Delta\epsilon/2) < 0.00613$
Nearly complete relaxation
for $(\Delta\epsilon/2) \geq 0.00613$

Specimen Details: Unnotched
0.250-inch diameter

Surface Condition: Polished, final surface finish unspecified

References: 3.7.3.2.8(d) and (e)

Test Parameters:
Loading – Axial, Triangular Waveform
Frequency – 0.50 Hz
Temperature – RT
Environment – Air

Equivalent Strain Equation:

$$\log (N_f) = -7.734 - 5.119 \log (\epsilon_{eq} - 0.0018)$$

$$\epsilon_{eq} = (\Delta\epsilon)^{0.61}\ (S_{max}/E)^{0.39}$$

Std. Error of Estimate, Log (Life) = 0.301
Standard Deviation, Log (Life) = 1.573
R^2 = 96.3%

Sample Size = 53

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios beyond those represented above.]

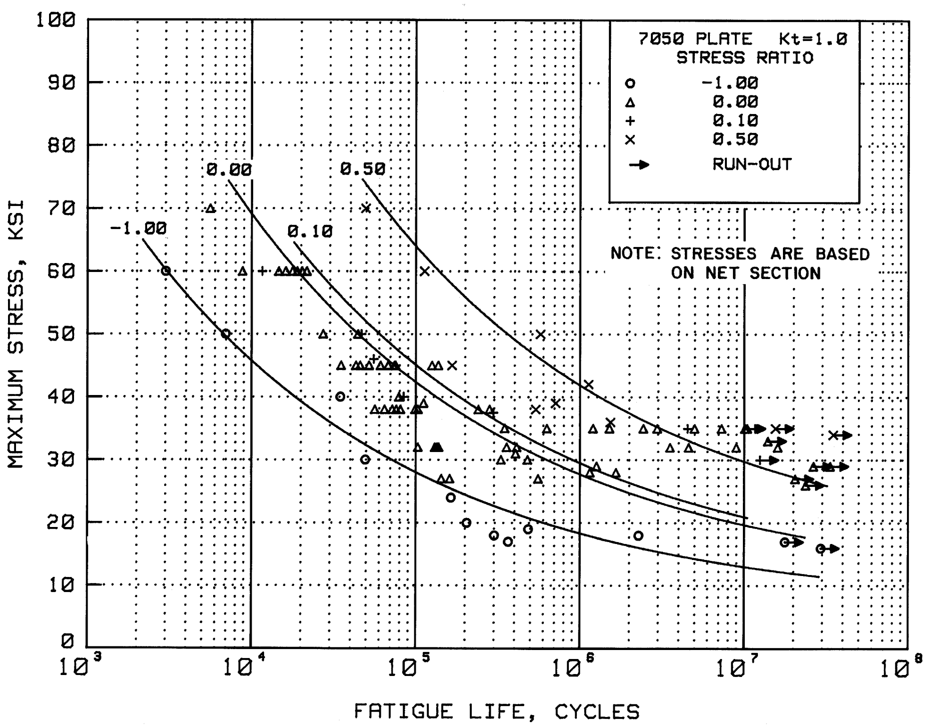


Figure 3.7.4.2.8(e). Best-fit S/N curves for unnotched 7050-T7451 plate, long transverse direction, t/4 specimen location.

Correlative Information for Figure 3.7.4.2.8(e)

Product Form: Plate, 1.0 to 6.0 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	73-81	62-72	RT

Specimen Details: Unnotched
0.250- and 0.300-inch diameter

Surface Condition: Not specified

References: 3.7.4.2.9(b), 3.7.8.2.8(b) and (e)

Test Parameters:
Loading - Axial
Frequency - 800 cpm and unspecified
Temperature - RT
Environment - Air

No. of Heats/Lots: 15

Equivalent Stress Equation:
Log N_f = 10.7-3.81 log (S_{eq}-10)
$S_{eq} = S_{max}(1-R)^{0.59}$
Std. Error of Estimate, Log (Life) = 0.507
Standard Deviation, Log (Life) = 0.794
R^2 = 59%

Sample Size = 85

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

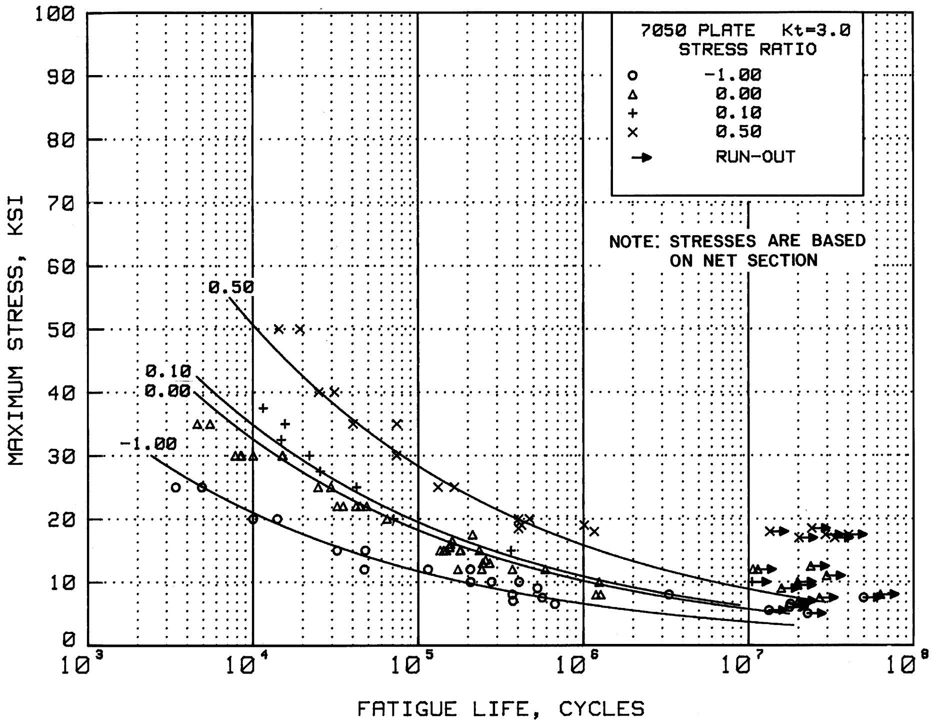


Figure 3.7.4.2.8(f). Best-fit S/N curves for notched, K_t = 3.0, 7050-T7451 plate, longitudinal and long transverse directions, t/4 specimen location.

Correlative Information for Figure 3.7.4.2.8(f)

Product Form: Plate, 1.0 to 6.0-inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	75-81	65-72	RT

Specimen Details:
Circumferentially notched, K_t = 3.0
0.306- and 0.373-inch gross diameter
0.253-inch net diameter
0.013-inch notch-tip radius, r
60° flank angle, ω

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.8.2.8(b) and (c)

Test Parameters:
Loading - Axial
Frequency - 800 cpm and unspecified
Temperature - RT
Environment - Air

No. of Heats/Lots: 11

Equivalent Stress Equation:
Log N_f = 10.0-3.96 log (S_{eq})
$S_{eq} = S_{max} (1-R)^{0.64}$
Std. Error of Estimate, Log (Life) = 0.248
Standard Deviation, Log (Life) = 0.728
R^2 = 88%

Sample Size = 79

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

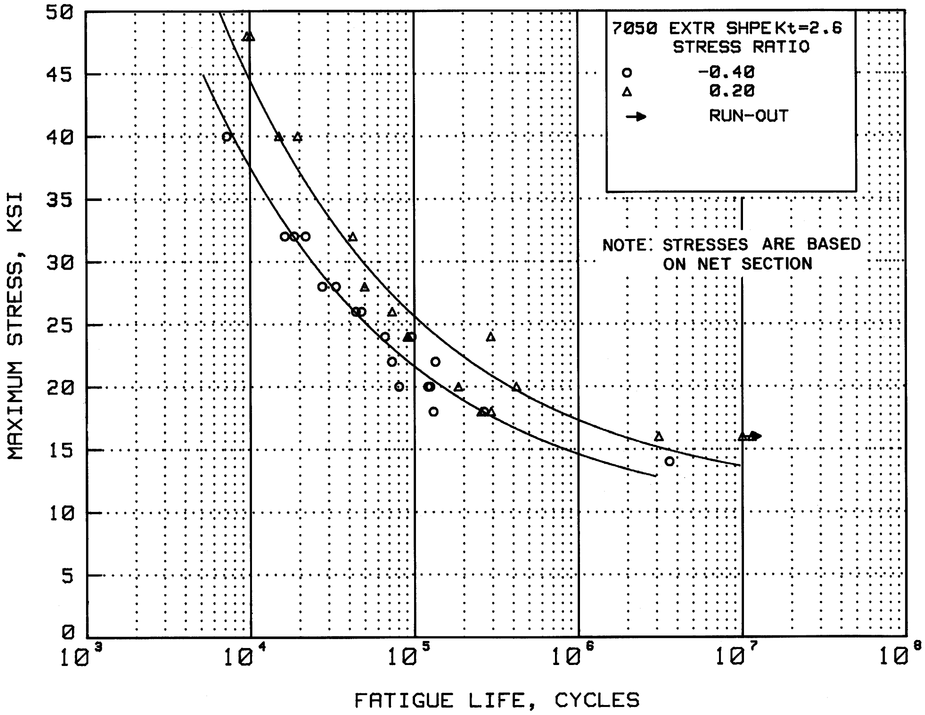


Figure 3.7.4.2.8(g). Best-fit S/N curves for notched, K_t = 2.6, 7050-T7451X extruded shape, longitudinal direction.

Correlative Information for Figure 3.7.4.2.8(g)

Product Form: Extruded shape, 0.5 to 5.0-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
76-77	67-68	RT

Specimen Details:
Notched, center hole, K_t = 2.6
0.150-inch diameter
0.250-inch thick
1.00-inch wide

Surface Condition: Not specified

Reference: 3.7.4.2.8(a)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - RT
Environment - Air

No. of Heats/Lots: 6

Equivalent Stress Equation:
Log N_f = 8.23-2.82 log (S_{eq}-10)
$S_{eq} = S_{max}$ $(1\text{-}R)^{0.30}$
Std. Error of Estimate, Log (Life) = 0.243
Standard Deviation, Log (Life) = 0.724
R^2 = 89%

Sample Size = 34

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

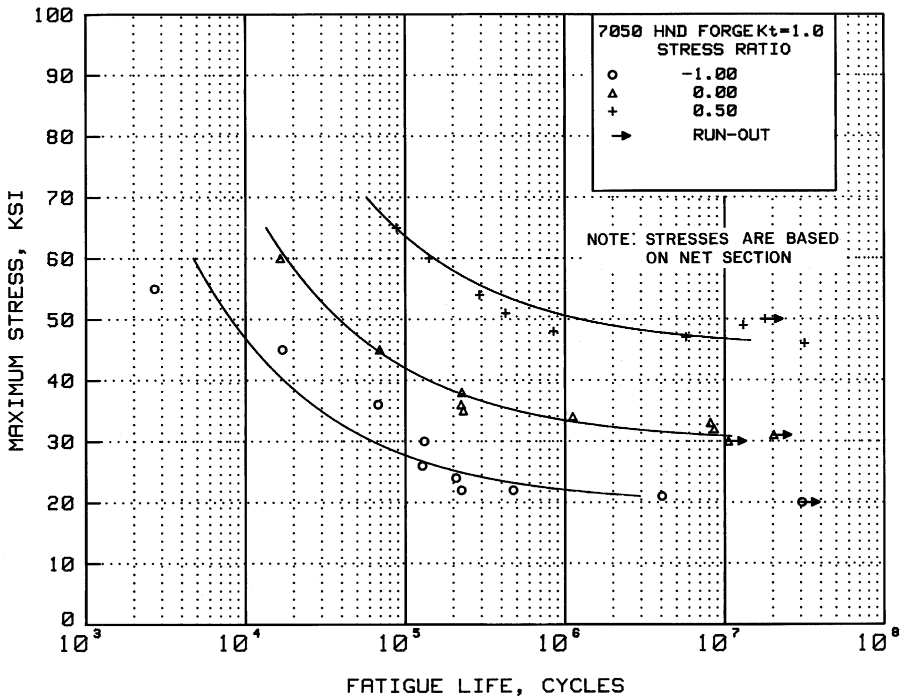


Figure 3.7.4.2.8(h). Best-fit S/N curves for unnotched 7050-T7452 hand forgings, longitudinal direction.

Correlative Information for Figure 3.7.4.2.8(h)

Product Form: Hand forgings, 2.0 to 8.0-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
76-81	66-72	RT

Specimen Details: Unnotched
0.300-inch diameter

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f = 7.06-1.89 log (S_{eq}-30)
$S_{eq} = S_{max}\ (1\text{-}R)^{0.60}$
Std. Error of Estimate, Log (Life) = 0.400
Standard Deviation, Log (Life) = 0.982
R^2 = 83%

Sample Size = 25

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

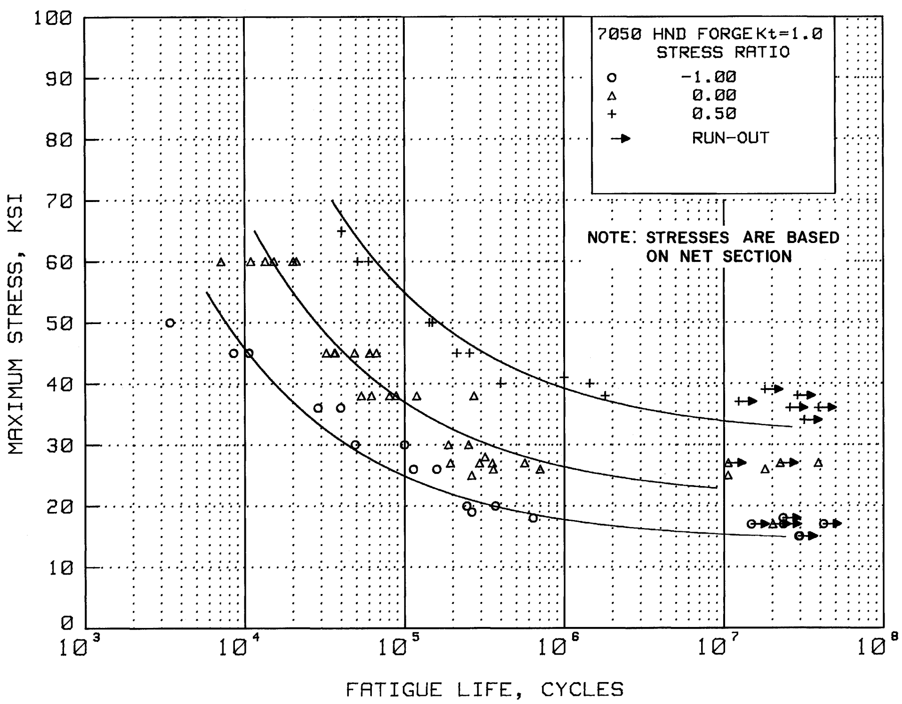


Figure 3.7.4.2.8(i). Best-fit S/N curves for unnotched 7050-T7452 hand forgings, long transverse and short transverse directions.

Correlative Information for Figure 3.7.4.2.8(i)

Product Form: Hand forgings, 2.0 to 8.0-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	73-80	59-70	RT

Specimen Details: Unnotched
0.300-inch diameter

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.8.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm and unspecified
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f = 7.58-2.14 log (S_{eq}-21)
$S_{eq} = S_{max}\ (1\text{-}R)^{0.57}$
Std. Error of Estimate, Log (Life) = 0.400
Standard Deviation, Log (Life) = 0.803
R^2 = 75%

Sample Size = 55

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

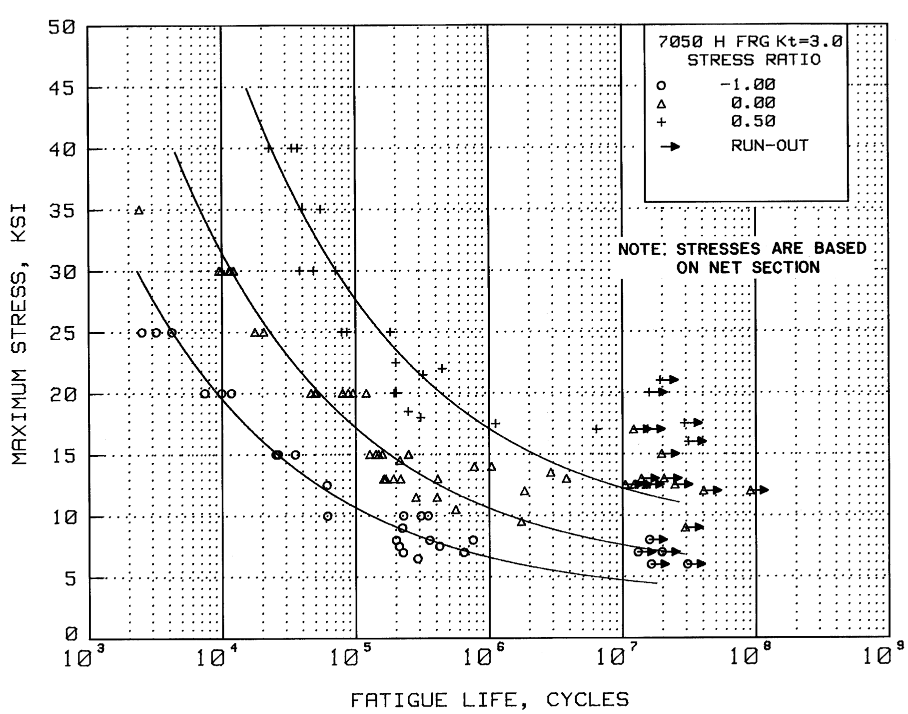


Figure 3.7.4.2.8(j). Best-fit S/N curves for notched, K_t = 3.0, 7050-T7452 hand forgings, longitudinal, long transverse, and short transverse directions.

Correlative Information for Figure 3.7.4.2.8(j)

Product Form: Hand forgings, 2.0 to 8.0-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
73-81	59-72	RT

Specimen Details:
Circumferentially notched, K_t = 3.0
0.306-inch gross diameter
0.253-inch net diameter
0.013-inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.8.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
$\text{Log } N_f = 8.21 - 2.96 \log (S_{eq} - 5)$
$S_{eq} = S_{max} (1-R)^{0.68}$
Std. Error of Estimate, Log (Life) = 0.307
Standard Deviation, Log (Life) = 0.735
R^2 = 83%

Sample Size = 80

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

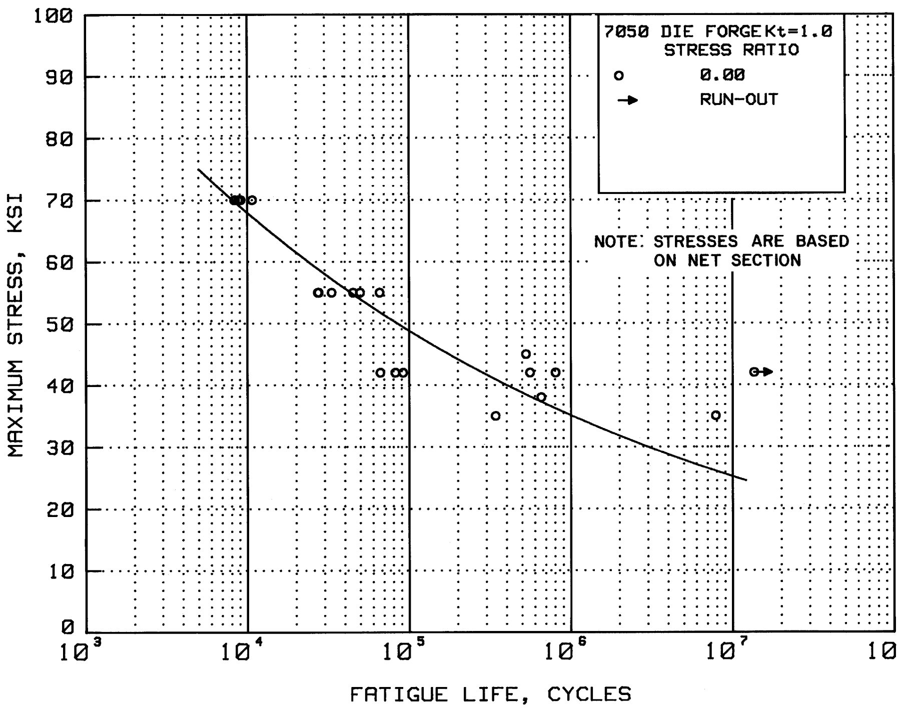


Figure 3.7.4.2.8(k). Best-fit S/N curves for unnotched 7050-T74 die forging, longitudinal directions.

Correlative Information for Figure 3.7.4.2.8(k)

Product Form: Die forging

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	74-81	68-71	RT

Specimen Details: Unnotched
0.300-inch diameter

Surface Condition: Not specified

References: 3.7.4.2.9(b) and 3.7.8.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 4

Equivalent Stress Equation:
Log N_f = 16.8-6.97 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.381
Standard Deviation, Log (Life) = 0.820
R^2 = 78%

Sample Size = 20

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

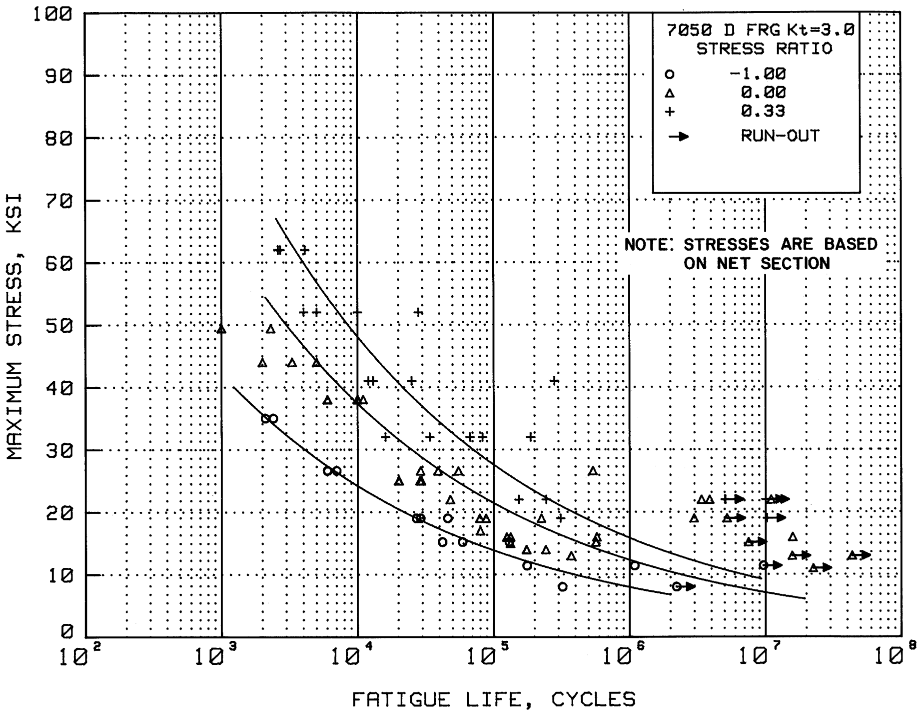


Figure 3.7.4.2.8(l). Best-fit S/N curves for notched, K_t = 3.0, 7050-T74 die forging, longitudinal direction.

Correlative Information for Figure 3.7.4.2.8(l)

Product Form: Die forging

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	77-81	68-71	RT

Specimen Details:
Circumferentially notched, K_t = 3.0
0.306- and 0.305-inch gross diameter
0.253- or 0.222-inch net diameter
0.013- or 0.012-inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

References: 3.7.4.2.8(b), 3.7.4.2.9(b), and 3.7.8.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800, 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 6

Equivalent Stress Equation:
Log N_f = 10.5-4.14 log (S_{eq})
$S_{eq} = S_{max}\,(1\text{-}R)^{0.629}$
Std. Error of Estimate, Log (Life) = 0.506
Standard Deviation, Log (Life) = 0.896
R^2 = 68%

Sample Size = 73

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

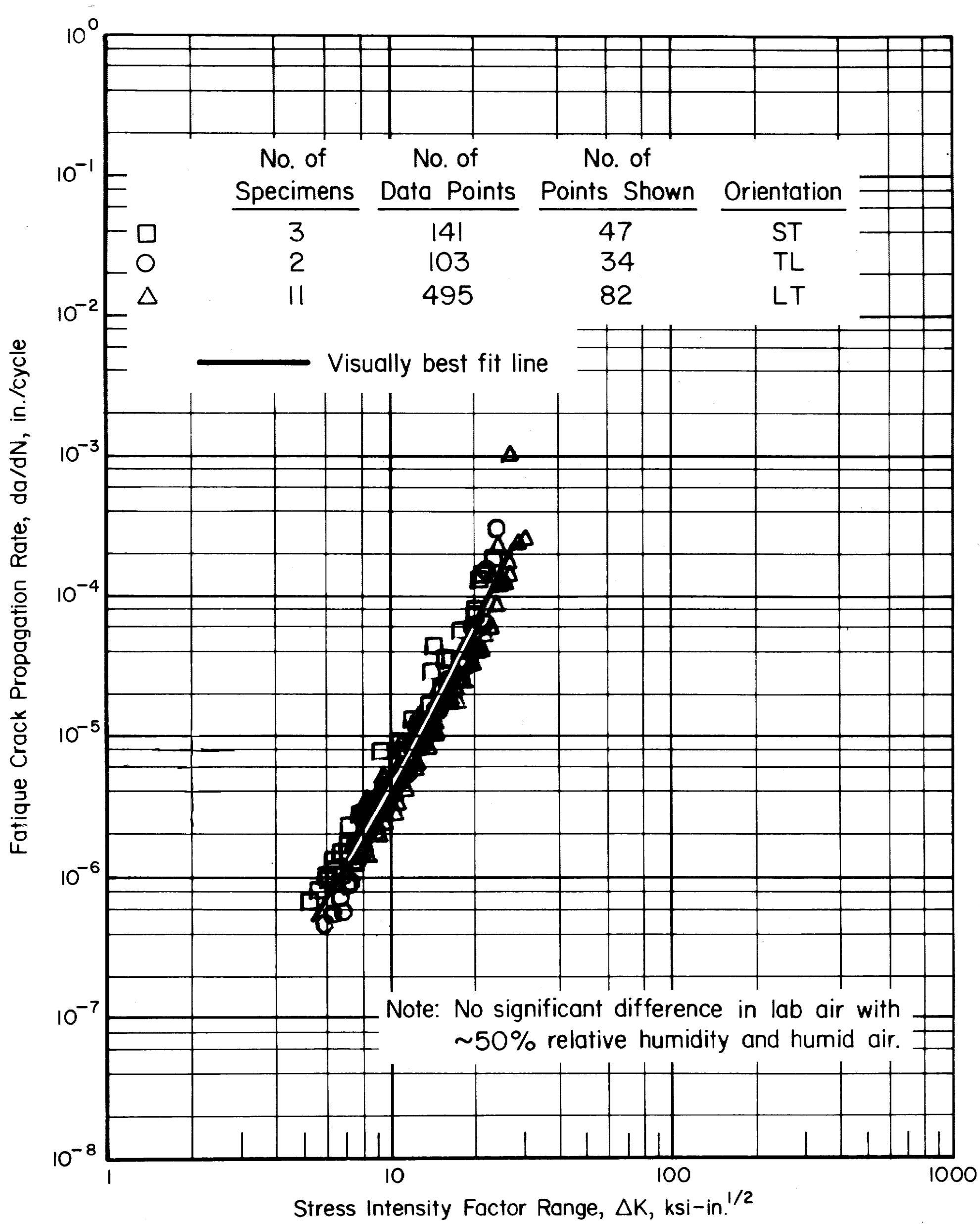


Figure 3.7.4.2.9(a). Fatigue-crack-propagation data for 3.15-inch-thick 7050-T7451 aluminum plate [Reference 3.7.4.2.9(a)].

Specimen Thickness:	*0.499-0.500 inch*	*Environment:*	*Lab air (~50% humidity) and humid air (100% humidity)*
Specimen Width:	*2.989-3.000 inches*		
Specimen Type:	*C(T)*	*Temperature:*	*RT*
Stress Ratio, R:	*0.1*	*Frequency, f:*	*10-20 Hz*

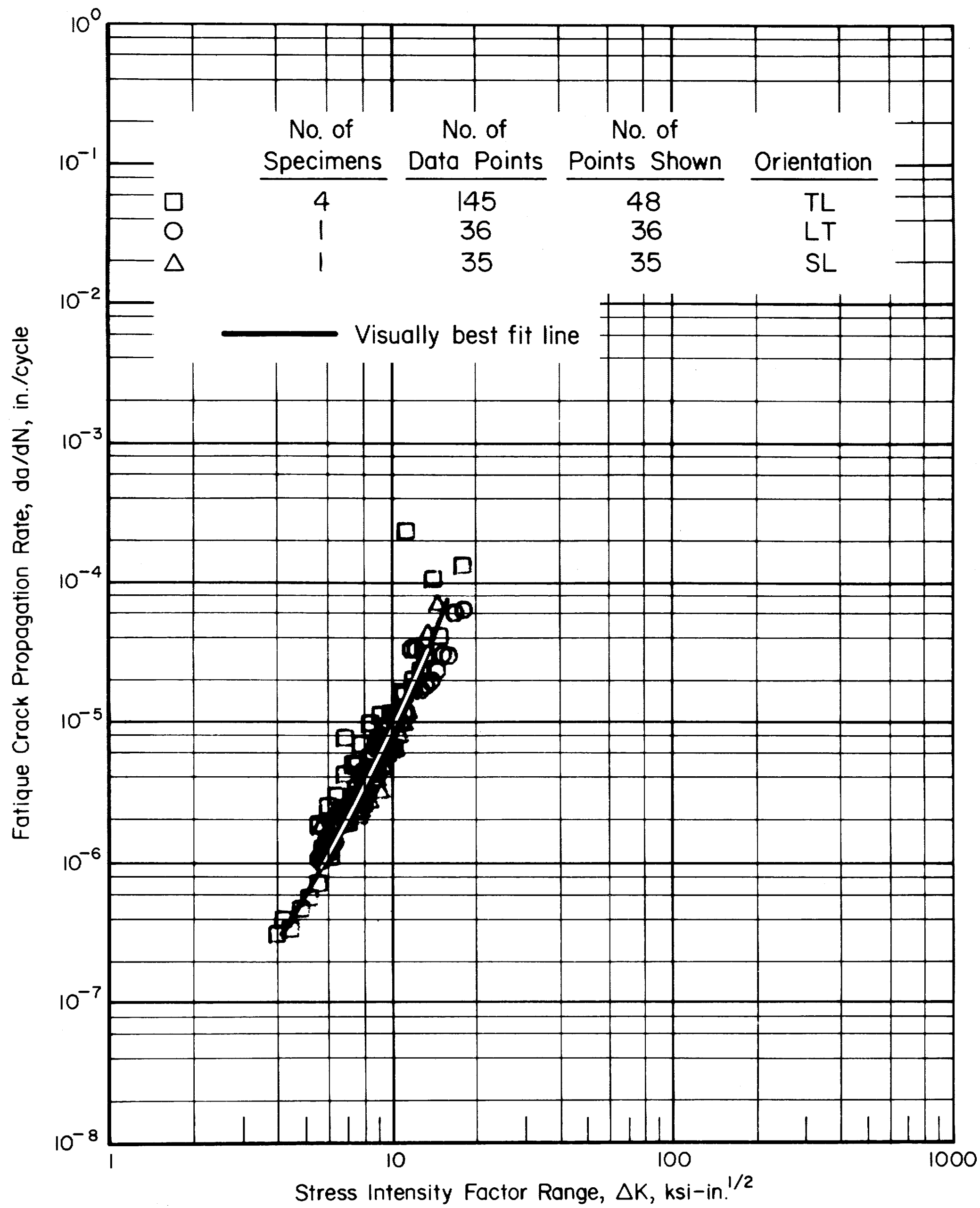


Figure 3.7.4.2.9(b). Fatigue-crack-propagation data for 1- and 6-inch-thick 7050-T7451 aluminum plate [Reference 3.7.4.2.9(b)].

Specimen Thickness:	*0.999-1.000 inch*	*Environment:*	*Dry air (< 10% humidity)*
Specimen Width:	*3.805 inches*	*Temperature:*	*RT*
Specimen Type:	*C(T)*	*Frequency, f:*	*18.3 Hz*
Stress Ratio, R:	*0.33*		

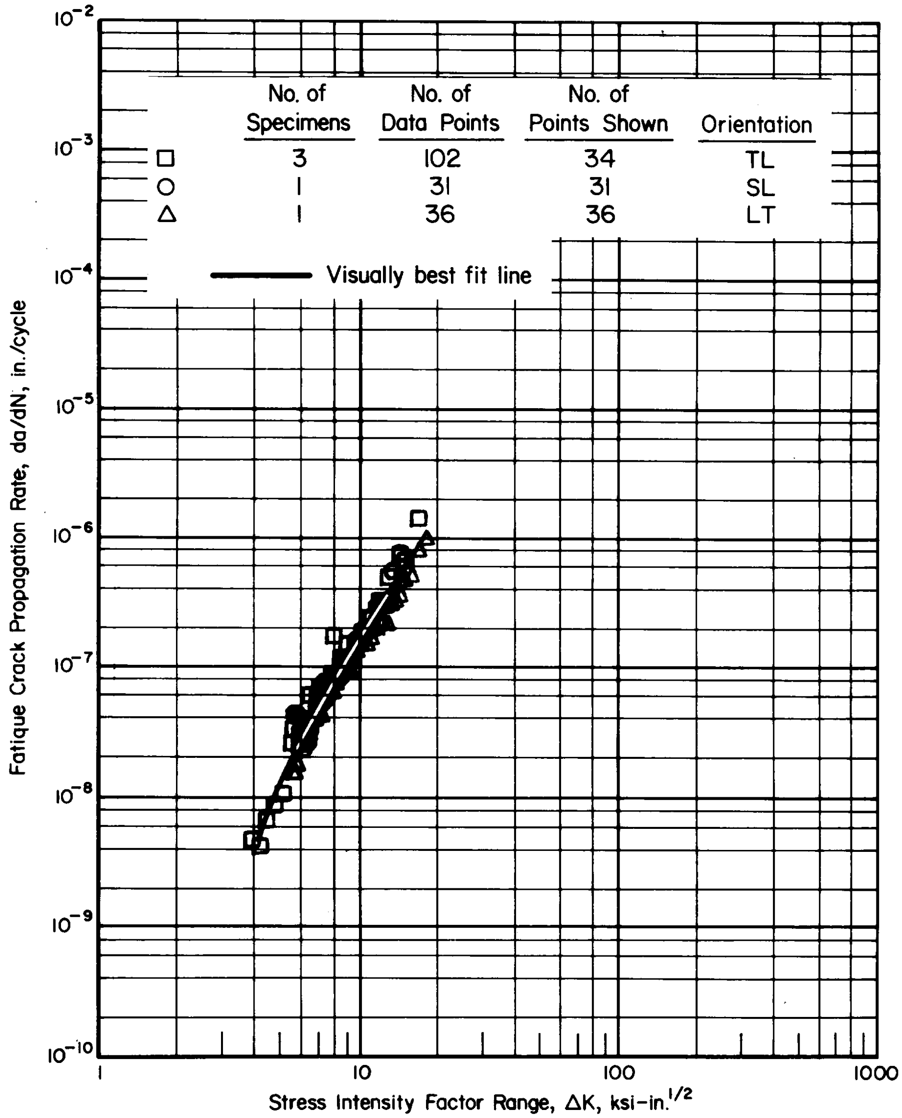


Figure 3.7.4.2.9(c). Fatigue-crack-propagation data for 1- and 6-inch-thick 7050-T7451 aluminum plate [Reference 3.7.4.2.9(b)].

Specimen Thickness:	*0.998-1.000 inch*	*Environment:*	*Humid air (>90% humidity)*
Specimen Width:	*3.805 inches*	*Temperature:*	*RT*
Specimen Type:	*C(T)*	*Frequency, f:*	*18.3 Hz*
Stress Ratio, R:	*0.33*		

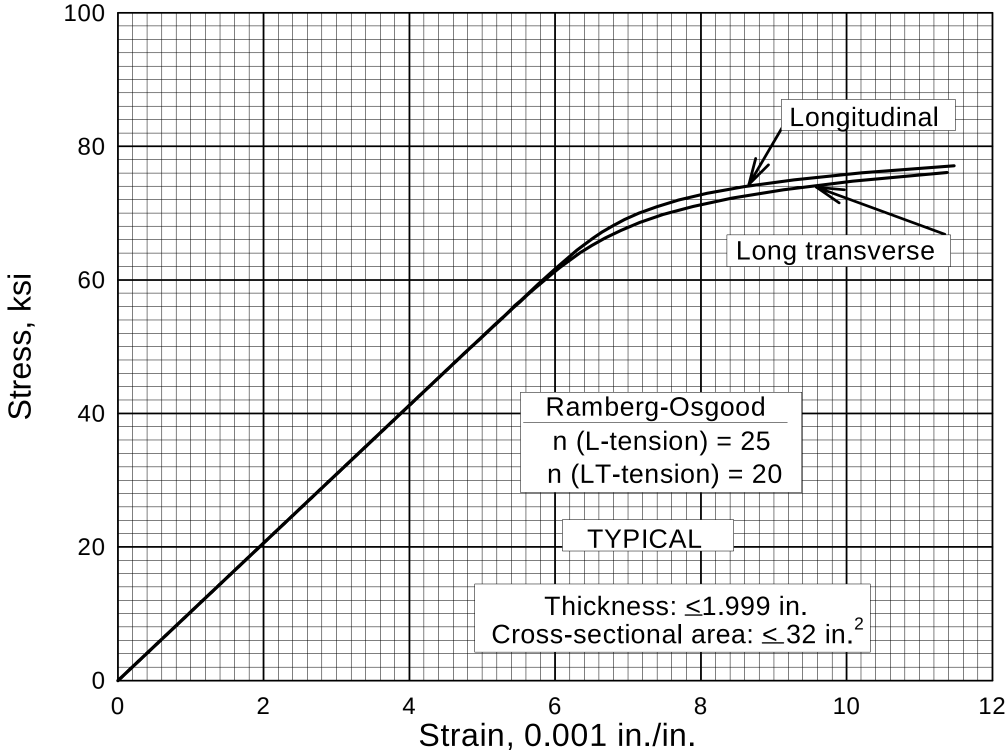


Figure 3.7.4.3.6(a). Typical tensile stress-strain curves for 7050-T7651X aluminum alloy extrusion at room temperature.

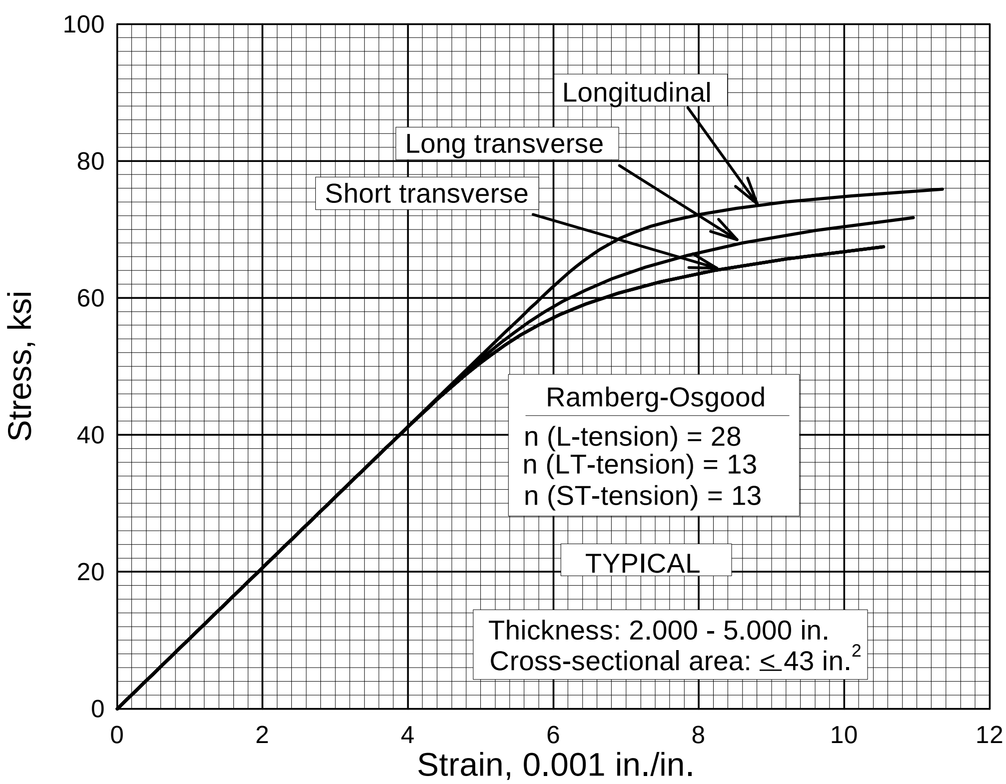


Figure 3.7.4.3.6(b). Typical tensile stress-strain curves for 7050-T7651X aluminum alloy extrusion at room temperature.

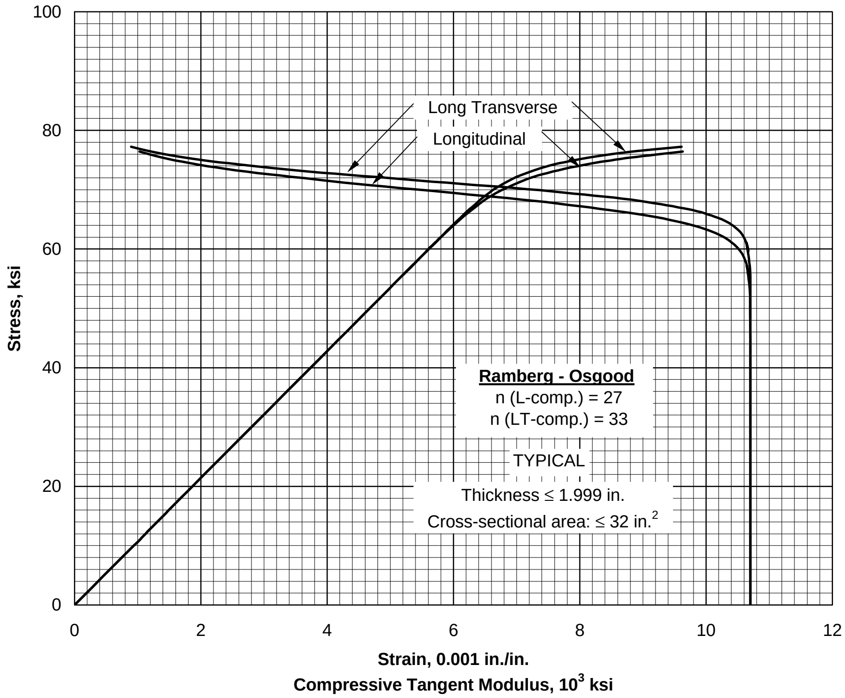


Figure 3.7.4.3.6(c). Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7651X aluminum alloy extrusion at room temperature.

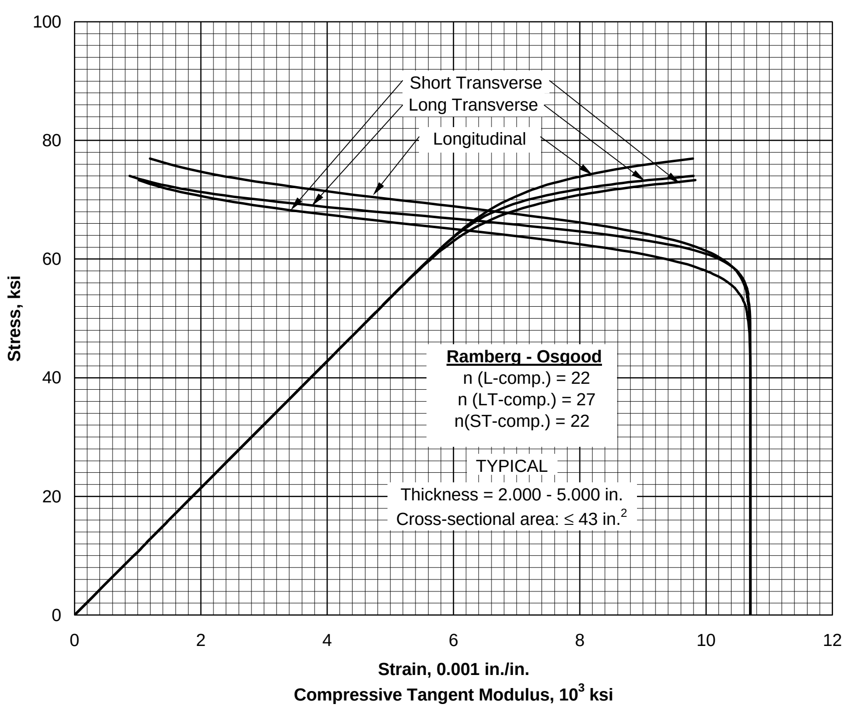


Figure 3.7.4.3.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7651X aluminum alloy extrusion at room temperature.

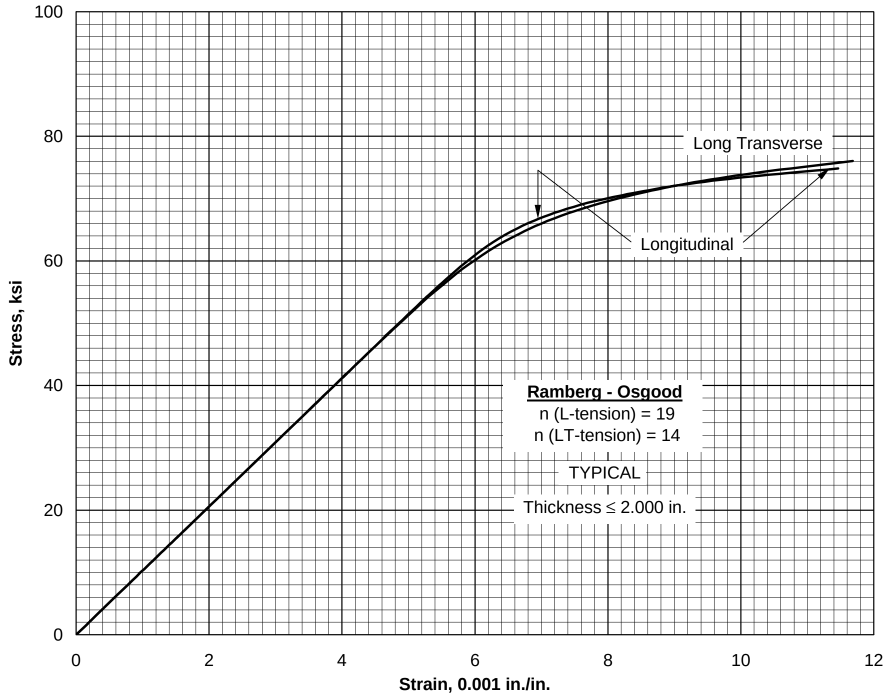


Figure 3.7.4.3.6(e). Typical tensile stress-strain curves for 7050-T7651 aluminum alloy plate at room temperature.

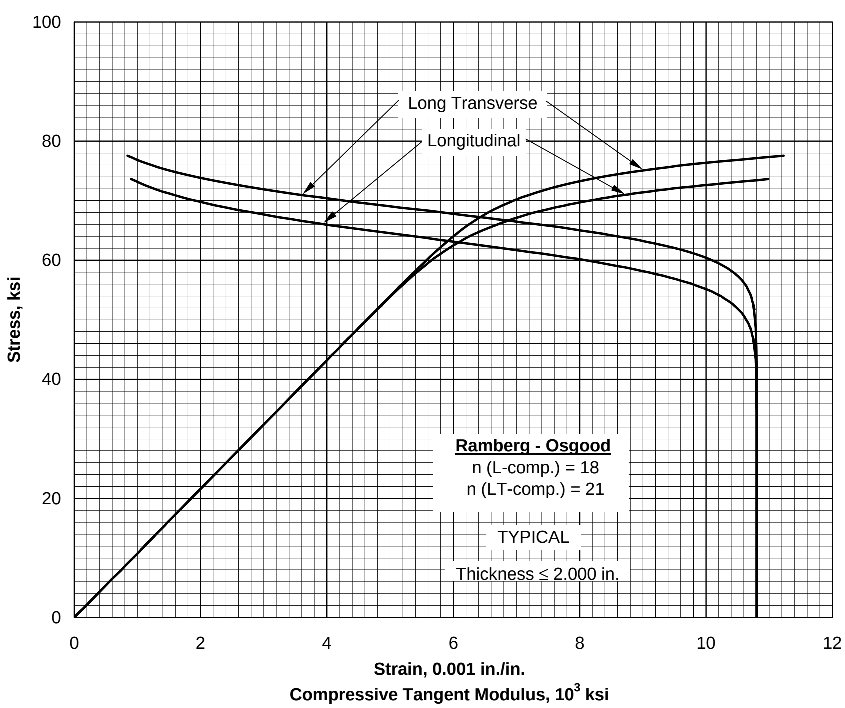


Figure 3.7.4.3.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for 7050-T7651 aluminum alloy plate at room temperature.

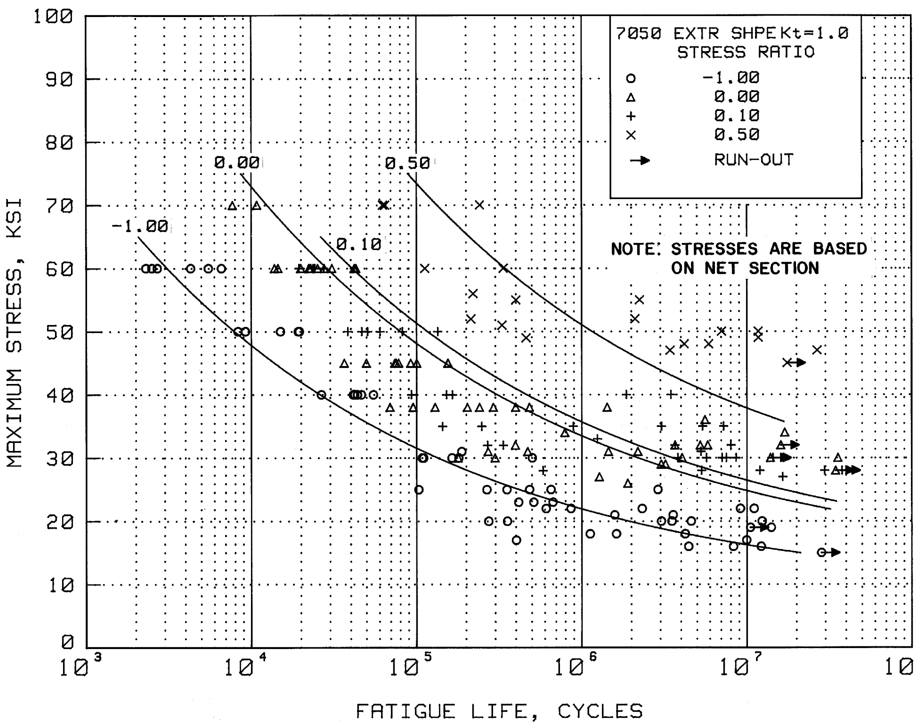


Figure 3.7.4.3.8(a). Best-fit S/N curves for unnotched 7050-T7651X extruded shape, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.4.3.8(a)

Product Form: Extruded shape, 0.5 to 5.0-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
84-90	75-81	RT

Specimen Details: Unnotched
0.300-inch diameter

Surface Condition: Not specified

References: 3.7.4.3.8(b), 3.7.4.2.9(b), and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f = 11.8-4.38 log (S_{eq}-12)
$S_{eq} = S_{max}$ $(1\text{-}R)^{0.61}$
Std. Error of Estimate, Log (Life) = 0.493
Standard Deviation, Log (Life) = 1.01
R^2 = 76%

Sample Size = 161

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

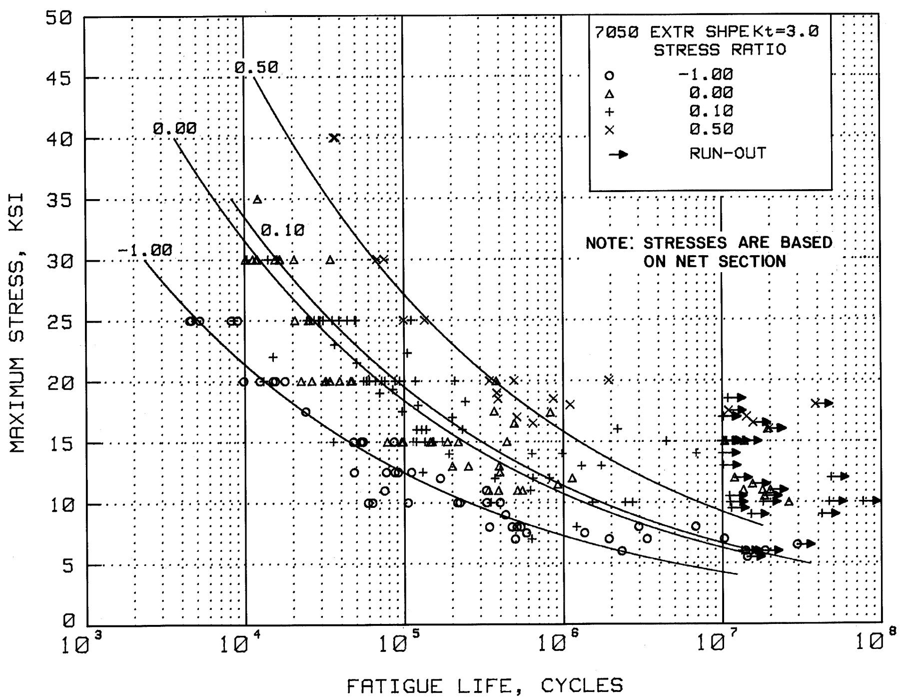


Figure 3.7.4.3.8(b). Best-fit S/N curves for notched, K_t = 3.0, 7050-T7651X extruded shape, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.4.3.8(b)

Product Form: Extruded shape, 0.5 to 5.0-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
78-90	68-81	RT

Specimen Details:
Circumferentially notched, K_t = 3.0
0.359-inch gross diameter
0.253-inch net diameter
0.013-inch root radius, r
60° flank angle, ω

Surface Condition: Not specified

References: 3.7.4.2.9(b), 3.7.4.3.8(a), and 3.7.7.2.8(b)

Test Parameters:
Loading - Axial
Frequency - 800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f = 10.38-4.26 log (Seq)
$S_{eq} = S_{max}\ (1-R)^{0.563}$
Std. Error of Estimate, Log (Life) = 0.398
Standard Deviation, Log (Life) = 0.778
R^2 = 74%

Sample Size = 179

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

3.7.5 7055 ALLOY

3.7.5.0 *Comments and Properties* — 7055 is an Al-Zn-Mg-Cu-Zr alloy and provides higher strength properties than 7150. 7055 is available in the form of plate and extrusions. The T77-type temper provides high tensile and compressive strength with guaranteed toughness (plate only) and exfoliation corrosion resistance. The T77-type temper has exfoliation corrosion resistance comparable to the T76-type temper of other 7XXX series aluminum alloys.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be overstated; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Materials specifications for 7055 are shown in Table 3.7.5.0(a). Room-temperature mechanical properties are presented in Tables 3.7.5.0(b) and 3.7.5.0(c).

Table 3.7.5.0(a). Material Specifications for 7055 Aluminum Alloy

Specification	Form
AMS 4206 (T7751)	Plate
AMS 4337 (T77511)	Extrusion

The temper index for 7055 is as follows:

Section	Temper
3.7.5.0	T7751 and T77511

Table 3.7.5.0(b) Design Mechanical and Physical Properties of 7055-T7751 Aluminum Alloy Plate

Specification	AMS 4206	
Form	Plate	
Temper	T7751	
Thickness, in.	0.500 - 1.500	
Basis	A	B
Mechanical Properties:		
F_{tu}, ksi:		
L	89	91
LT	89	91
F_{ty}, ksi:		
L	86	88
LT	85	87
F_{cy}, ksi:		
L	86	88
LT	89	91
F_{su},[a] ksi	48	49
F_{bru},[b] ksi:		
(e/D = 1.5)	128	131
(e/D = 2.0)	167	170
F_{bry},[b] ksi:		
(e/D = 1.5)	112	115
(e/D = 2.0)	130	133
e, percent (S-basis):		
L	7	...
LT	8	...
E, 10^3 ksi	10.4	
E_c, 10^3 ksi	10.7	
G, 10^3 ksi	3.9	
μ	0.32	
Physical Properties:		
ω, lb/in.^{3}	0.103	
C, Btu/(lb)(°F)	...	
K, Btu/[(hr)(ft^2)(°F)/ft]	...	
α, 10^{-6} in./in./°F	...	

a Determined in accordance with ASTM B769.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.5.0(c) Design Mechanical and Physical Properties of 7055-T77511 Aluminum Alloy Extrusion

Specification	AMS 4337	
Form	Extrusion	
Cross-sectional area, in^2		
Temper	T77511	
Thickness, in.	0.500 - 1.500	
Basis	A	B
Mechanical Properties:		
F_{tu}, ksi:		
L	94	95
LT	88	90
F_{ty}, ksi:		
L	90	93
LT	84[a]	88
F_{cy}, ksi:		
L	92	94
LT	89	92
F_{su},[b] ksi	48	49
F_{bru},[c] ksi:		
(e/D = 1.5)	128	131
(e/D = 2.0)	167	169
F_{bry},[c] ksi:		
(e/D = 1.5)	109	113
(e/D = 2.0)	131	135
e, percent (S-basis):		
L	9	
LT	5	
E, 10^3 ksi	10.4	
E_c, 10^3 ksi	11.0	
G, 10^3 ksi	...	
μ	0.33	
Physical Properties:		
ω, lb/in.^{3}	0.103	
C, Btu/(lb)(°F)	...	
K, Btu/[(hr)(ft^2)(°F)/ft]	...	
α, 10^{-6} in./in./°F	...	

a S-basis. The T_{99} value is 85.86 ksi.
b Determined in accordance with ASTM B769.
c Bearing values are "dry pin" values per Section 1.4.7.1.

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3.7.6 7075 ALLOY

3.7.6.0 *Comments and Properties* — 7075 is a high-strength Al-Zn-Mg-Cu alloy and is available in a wide variety of product forms. It is also available in several types of tempers, the T6, T73, and T76 type. The T6 temper has the highest strength but lowest toughness and resistance to stress-corrosion cracking. Since toughness decreases with a decrease in temperature, the T6 temper is not generally recommended for cryogenic applications. As shown in Table 3.1.2.3.1(a), 7075-T6 rolled plate, rod and bar, extruded shapes, and forgings have a 'D' SCC rating. This is the lowest rating and means that SCC failures have occurred in service or would be anticipated if there is any sustained stress. In-service failures are caused by stressed produced by any combination of sources including solution heat treatment, straightening, forming, fit-up, clamping, sustained service loads or high service compression stresses that produce residual tensile stresses. These stresses may be tension or compression as well as the stresses due to the Poisson effect, because the actual failures are caused by the resulting sustained shear stresses. Pin-hole flaws in corrosion protection are sufficient for SCC. The T73 temper provides for much improved stress-corrosion resistance over T6 temper with a decrease in strength. The T76 temper provides for improved exfoliation resistance and limited stress-corrosion resistance over T6 temper with some decrease in strength. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking and to Section 3.1.3.4 for comments regarding the weldability of this alloy.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 7075 aluminum alloy are presented in Table 3.7.6.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.7.6.0(b_1) through (g_4). The effect of temperature on the physical properties of this alloy is presented in Figure 3.7.6.0.

Table 3.7.6.0(a). Material Specifications for 7075 Aluminum Alloy

Specification	Form
AMS 4044	Bare sheet and plate
AMS 4045	Bare sheet and plate
AMS 4078	Bare plate
AMS-QQ-A-250/12, 24	Bare sheet and plate
AMS-QQ-A-250/13, 25	Clad sheet and plate
AMS 4049	Clad sheet and plate
AMS 4122	Bar and rod, rolled or cold finished
AMS 4123	Bar and rod, rolled or cold finished
AMS 4124	Bar and rod, rolled or cold finished
AMS 4186	Bar and rod, rolled or cold finished
AMS 4187	Bar and rod, rolled or cold finished
AMS-QQ-A-225/9	Rolled or drawn bar and rod
AMS-QQ-A-200/11, 15	Extruded bar, rod, and shapes
AMS 4126	Forging
AMS 4141	Die forging
AMS 4147	Forging
AMS-A-22771	Forging
AMS-QQ-A-367	Forging

The temper index for 7075 is as follows:

Section	Temper
3.7.6.1	T6, T651, T652, T6510, T6511
3.7.6.2	T73, T7351, T7352, T73510, T73511

3.7.6.1 ***T6, T651, T652, T6510, T6511 Temper*** — Figures 3.7.6.1.1(a) and (b) permit calculation of residual tensile strengths for complex thermal exposure conditions. They are based upon the rate parameter T(C + log t), in which T is exposure temperature in degrees Rankine, t is exposure time in hours and C is a constant evaluated for each material. These curves have been verified for use only within the ranges of temperatures and exposure times covered in the figures. The following example illustrates their use.

Sample problem: Find F_{tu} at 250°F following a complex exposure of 300°F, 8 hours plus 350°F, 1 hour.

1. Reduce given complex exposure by converting 350°F exposure to equivalent exposure time at 300°F.*
   a. On the 350°F single exposure temperature line find 350°F, 1 hour.
   b. From this point move vertically to the 300°F exposure temperature line and then read right, 12 hours exposure.
   c. Total equivalent exposure time at 300°F is therefore 8 hours + 12 hours or 20 hours.
2. Find F_{tu} at 250°F following 300°F, 20 hours exposure:
   a. On the 300°F exposure temperature line find 300°F, 20 hours.
   b. From this point move vertically to the 250°F test temperature curve and then read left, 76 percent F_{tu}.

Solution: F_{tu} is 76 percent of the original room temperature F_{tu}. F_{ty} is determined in like manner. F_{cy} can be closely estimated by using the percent reduction factor determined for F_{ty}. For specific data, see Reference 3.7.6.1.

Stressed Thermal Exposure — Stress applied during sample and complex thermal exposure of 7075-T6 can have additional effect in reducing material strength. However, the effect becomes significant only when exposure strains exceed 0.2 percent. For specific data, see Reference 3.7.6.1.

Figures 3.7.6.1.1(c) through 3.7.6.1.5(b) present elevated temperature curves for various mechanical properties. Figures 3.7.6.1.6(a) through (m) present tensile and compressive stress-strain and tangent-modulus curves at several temperatures. Figures 3.7.6.1.6(n) through (q) are full-range stress-strain curves for various products. Figures 3.7.6.1.8(a) through (h) provide room-temperature fatigue curves for T6 temper products. Fatigue-crack propagation data for sheet are presented in Figure 3.7.6.1.9. Graphical displays of the residual strength behavior of center-cracked tension panels are presented in Figure 3.7.6.1.10(a) through (h).

3.7.6.2 ***T73, T7351, T7352, T73510, T73511 Tempers*** — Figures 3.7.6.2.6(a) through (d) present stress-strain and tangent-modulus curves for various products and tempers. Figures 3.7.6.2.6(e) and (f) are full-range stress-strain curves at room temperature for extrusion. Fatigue-crack-propagation data for plate are presented in Figures 3.7.6.2.9(a) through (c). Graphical displays of the residual strength behavior of center-cracked tension panels are presented in Figures 3.7.6.2.10(a) and (b).

---

* Choice of reference temperature is optional as long as it permits computation within the bounds of the figures.

Table 3.7.6.0(b_1). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Sheet and Plate

Specification	AMS 4045 and AMS-QQ-A-250/12																				
Form	Sheet							Plate													
Temper	T6 and T62[a]							T651													
Thickness, in.	0.008-0.011	0.012-0.039		0.040-0.125		0.126-0.249		0.250-0.499		0.500-1.000		1.001-2.000		2.001-2.500		2.501-3.000		3.001-3.500		3.501-4.000	
Basis	S	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																					
F_{tu}, ksi:																					
L	...	76	78	78	80	78	80	77	79	77	79	76	78	75	77	71	73	70	72	66	68
LT	74	76	78	78	80	78	80	78	80	78	80	77	79	76	78	72	74	71	73	67	69
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	70[b]	71[b]	66[b]	68[b]	65[b]	67[b]	61[b]	63[b]
F_{ty}, ksi:																					
L	...	69	72	70	72	71	73	69	71	70	72	69	71	66	68	63	65	60	62	56	58
LT	63	67	70	68	70	69	71	67	69	68	70	67	69	64	66	61	63	58	60	54	56
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	59[b]	61[b]	56[b]	58[b]	54[b]	55[b]	50[b]	52[b]
F_{cy}, ksi:																					
L	...	68	71	69	71	70	72	67	69	68	70	66	68	62	64	58	60	55	57	51	52
LT	...	71	74	72	74	73	75	71	73	72	74	71	73	68	70	65	67	61	64	57	59
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	67	70	64	66	61	63	57	59
F_{su}, ksi	...	46	47	47	48	47	48	43	44	44	45	44	45	44	45	42	43	42	43	39	41
F_{bru}[c], ksi:																					
(e/D = 1.5)	...	118	121	121	124	121	124	117	120	117	120	116	119	114	117	108	111	107	110	101	104
(e/D = 2.0)	...	152	156	156	160	156	160	145	148	145	148	143	147	141	145	134	137	132	135	124	128
F_{bry}[c], ksi:																					
(e/D = 1.5)	...	100	105	102	105	103	106	97	100	100	103	100	103	98	101	94	97	89	93	84	87
(e/D = 2.0)	...	117	122	119	122	121	124	114	118	117	120	117	120	113	117	109	112	104	108	98	103
e, percent (S-basis):																					
LT	5	7	...	8	...	8	...	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi	10.3							10.3													
E_c, 10^3 ksi	10.5							10.6													
G, 10^3 ksi	3.9							3.9													
μ	0.33							0.33													
Physical Properties:																					
ω, lb/in.^{3}	0.101																				
C, K, and α	See Figure 3.7.6.0																				

a Design allowables were based upon data obtained from testing T6 temper sheet and from testing samples of sheet, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.

b Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

c Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.6.0(b$_2$). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Plate—Continued

Specification	AMS 4044 and AMS-QQ-A-250/12						AMS-QQ-A-250/12							
Form	Plate													
Temper	T62[a]													
Thickness, in.	0.250-0.499		0.500-1.000		1.001-2.000		2.001-2.500		2.501-3.000		3.001-3.500		3.501-4.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:														
F_{tu}, ksi:														
L	74	76	74	76	73	75	72	74	69	71	68	70	64	66
LT	78	80	78	80	77	79	76	78	72	74	71	73	67	69
ST	...	...	...	...	...	...	70[b]	71[b]	66[b]	68[b]	65[b]	67[b]	61[b]	63[b]
F_{ty}, ksi:														
L	65	67	66	68	64	65	60	62	56	58	52	54	48	49
LT	67	69	68	70	67	69	64	66	61	63	58	60	54	56
ST	...	...	...	...	...	...	59[b]	61[b]	56[b]	58[b]	54[b]	55[b]	50[b]	52[b]
F_{cy}, ksi:														
L	70	72	70	72	68	70	63	65	59	61	55	57	50	52
LT	70	72	71	73	68	71	65	67	61	63	57	59	52	54
ST	...	...	...	...	...	...	63	65	60	62	57	59	53	55
F_{su}, ksi	43	44	44	45	44	45	44	45	42	43	42	43	39	41
F_{bru}[c], ksi:														
(e/D = 1.5)	117	120	117	120	116	119	114	117	108	111	107	110	101	104
(e/D = 2.0)	145	148	145	148	143	147	141	145	134	137	132	135	124	128
F_{bry}[c], ksi:														
(e/D = 1.5)	97	100	100	103	100	103	98	101	94	97	89	93	84	87
(e/D = 2.0)	114	118	117	120	117	120	113	117	109	112	104	108	98	103
e, percent (S-basis):														
LT	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi	10.3													
E_c, 10^3 ksi	10.6													
G, 10^3 ksi	3.9													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.7.6.0													

a Design allowables were based upon data obtained from testing samples of plate, supplied in O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.
b Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).
c Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.6.0(b$_3$). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/12	AMS 4078 and AMS-QQ-A-250/12												
Form	Sheet	Plate												
Temper	T73	T7351												
Thickness, in.	0.040-0.249	0.250-0.499	0.500-1.000		1.001-1.500		1.501-2.000		2.001-2.500		2.501-3.000		3.001-3.500	3.501-4.000
Basis	S	S	A	B	A	B	A	B	A	B	A	B	S	S
Mechanical Properties:														
F_{tu}, ksi:														
L	67	68	68	70	67	69	66	68	65	67	63	65	62	60
LT	67	69	69	71	68	70	67	69	66	68	64[a]	66	63	61
ST	...	...	...	...	...	...	63	65	62	64	60	62	59	57
F_{ty}, ksi:														
L	56	57	57	59	57	59	55	57	52	55	49	53	49	48
LT	56	57	57	59	57	59	55	57	52[b]	55	49[a]	53	49	48
ST	...	...	...	...	...	...	52	54	49	52	47	50	47	46
F_{cy}, ksi:														
L	55	56	56	58	56	58	53	55	50	53	47	51	47	45
LT	58	59	59	61	59	61	57	59	54	57	51	55	51	50
ST	...	...	...	...	...	...	59	61	55	58	51	55	50	48
F_{su}, ksi	38	38	38	39	38	40	39	40	39	40	38	39	38	37
F_{bru}[c], ksi:														
(e/D = 1.5)	105	102	103	106	103	106	102	106	102	105	100	103	99	96
(e/D = 2.0)	134	131	132	136	132	136	132	136	131	135	128	132	127	124
F_{bry}[c], ksi:														
(e/D = 1.5)	84	79	81	83	83	86	82	85	79	83	76	81	76	76
(e/D = 2.0)	102	95	97	100	99	102	97	101	93	99	89	96	89	88
e, percent (S-basis):														
LT	8	7	7	...	6	...	6	...	6	...	6	...	6	6
E, 10^3 ksi	10.3	10.3												
E_c, 10^3 ksi	10.5	10.6												
G, 10^3 ksi	3.9	3.9												
μ	0.33	0.33												
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.7.6.0													

a S-basis. The rounded T_{99} values are as follows: F_{tu}(LT) = 65 ksi and F_{ty}(LT) = 52 ksi.
b S-basis. The rounded T_{99} value is as follows: F_{ty}(LT) = 53 ksi.
c Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.6.0(b_4). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/24				
Form	Sheet and plate				
Temper	T76	T7651			
Thickness, in.	0.063-0.249	0.250-0.499	0.500-1.000	1.001-1.500	1.501-2.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	72	71	70	70	70
LT	73	72	71	71	71
ST	...	...	...	...	65
F_{ty}, ksi:					
L	62	60	59	59	59
LT	62	61	60	60	60
ST	...	...	...	...	56
F_{cy}, ksi:					
L	61	60	59	59	59
LT	65	64	63	63	63
ST	...	...	...	...	63
F_{su}, ksi	42	40	41	42	43
F_{bru}[a], ksi:					
(e/D = 1.5)	112	109	108	108	108
(e/D = 2.0)	145	141	140	140	140
F_{bry}[a], ksi:					
(e/D = 1.5)	88	86	86	86	87
(e/D = 2.0)	102	99	99	99	100
e, percent:					
LT	8	8	6	5	5
E, 10^3 ksi	10.3	10.3			
E_c, 10^3 ksi	10.5	10.6			
G, 10^3 ksi	3.9	3.9			
μ	0.33	0.33			
Physical Properties:					
ω, lb/in.^{3}	0.101				
C, K, and α	See Figure 3.7.6.0				

a Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.6.0(c_1). Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Sheet

Specification	AMS 4049								
Form	Sheet								
Temper	T6								
Thickness, in.	0.008-0.011	0.012-0.039		0.040-0.062		0.063-0.187		0.188-0.249	
Basis	S	A	B	A	B	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	...	71	74	71	75	74	77	75	77
LT	68	71	74	71	75	74[a]	77	75	77
F_{ty}, ksi:									
L	...	62	65	63	66	66	69	66	68
LT	58	60	63	61	64	64	67	64	66
F_{cy}, ksi:									
L	...	61	64	62	65	65	68	65	67
LT	...	64	67	65	68	68	71	68	70
F_{su}, ksi	...	42	44	42	45	44	46	45	46
F_{bru}[b], ksi:									
(e/D = 1.5)	...	110	115	110	116	115	119	116	119
(e/D = 2.0)	...	142	148	142	150	148	154	150	154
F_{bry}[b], ksi:									
(e/D = 1.5)	...	90	94	91	96	96	100	96	99
(e/D = 2.0)	...	105	110	106	112	112	117	112	115
e, percent (S-basis):									
LT	5	8	...	9	...	9	...	9	...
E, 10^3 ksi:									
Primary	10.3					10.3		10.3	
Secondary	9.5					9.8		10.0	
E_c, 10^3 ksi:									
Primary	10.5					10.5		10.5	
Secondary	9.7					10.0		10.2	
G, 10^3 ksi	...					...		...	
μ	0.33					0.33		0.33	
Physical Properties:									
ω, lb/in.^{3}	0.101								
C, K, and α	...								

a S-Basis. The rounded T_{99} value is 75 ksi.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.6.0(c_2). Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Sheet—Continued

Specification	AMS-QQ-A-250/13								
Form	Sheet								
Temper	T6 and T62[a]								
Thickness, in.	0.008-0.011	0.012-0.039		0.040-0.062		0.063-0.187		0.188-0.249	
Basis	S	A	B	A	B	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	...	70	74	71	75	73	77	75	77
LT	68	70[b]	74	71	75	73[c]	77	75	77
F_{ty}, ksi:									
L	...	62	65	63	66	65	69	66	68
LT	58	60	63	61	64	63[d]	67	64	66
F_{cy}, ksi:									
L	...	61	64	62	65	64	68	65	67
LT	...	64	67	65	68	67	71	68	70
F_{su}, ksi	...	42	44	42	45	44	46	45	46
F_{bru}[e], ksi:									
(e/D = 1.5)	...	108	115	110	116	113	119	116	119
(e/D = 2.0)	...	140	148	142	150	146	154	150	154
F_{bry}[e], ksi:									
(e/D = 1.5)	...	90	94	91	96	94	100	96	99
(e/D = 2.0)	...	105	110	106	112	110	117	112	115
e, percent (S-basis):									
LT	5	7	...	8	...	8	...	8	...
E, 10^3 ksi:									
Primary	10.3					10.3		10.3	
Secondary	9.5					9.8		10.0	
E_c, 10^3 ksi:									
Primary	10.5					10.5		10.5	
Secondary	9.7					10.0		10.2	
G, 10^3 ksi	...					...		...	
μ	0.33					0.33		0.33	
Physical Properties:									
ω, lb/in.^{3}	0.101								
C, K, and α	...								

a Design allowables were based upon data obtained from testing T6 temper sheet and from testing samples of sheet, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.
b S-Basis. The rounded T_{99} value is 71 ksi.
c S-Basis. The rounded T_{99} value is 75 ksi.
d S-Basis. The rounded T_{99} value is 64 ksi.
e Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.6.0(c_3). Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Plate—Continued

Specification	AMS 4049 and AMS-QQ-A-250/13													
Form	Plate													
Temper	T651													
Thickness, in.	0.250-0.499		0.500-1.000[a]		1.001-2.000[a]		2.001-2.500[a]		2.501-3.000[a]		3.001-3.500[a]		3.501-4.000[a]	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:														
F_{tu}, ksi:														
L	74	76	75	77	74	76	73	75	69	71	68	70	64	66
LT	75	77	76	78	75	77	74	76	70	72	69	71	65	67
ST	...	...	...	...	...	...	70[b]	71[b]	66[b]	68[b]	65[b]	67[b]	61[b]	63[b]
F_{ty}, ksi:														
L	67	69	68	70	67	69	64	66	61	63	58	60	54	56
LT	65	67	66	68	65	67	62	64	59	61	56	58	52	54
ST	...	...	...	...	...	...	59[b]	61[b]	56[b]	58[b]	54[b]	55[b]	50[b]	52[b]
F_{cy}, ksi:														
L	65	67	66	68	64	66	60	62	57	58	53	55	49	51
LT	69	71	70	72	69	71	65	68	62	64	59	61	55	57
ST	...	...	...	...	...	...	67	70	64	66	61	63	57	59
F_{su}, ksi	42	43	42	44	42	44	43	44	41	42	40	42	38	39
F_{bru}[c], ksi:														
(e/D = 1.5)	113	116	114	117	113	116	111	114	105	108	104	107	98	101
(e/D = 2.0)	139	143	141	145	139	143	137	141	130	134	128	132	121	124
F_{bry}[c], ksi:														
(e/D = 1.5)	94	97	97	100	97	100	95	98	90	94	86	89	80	84
(e/D = 2.0)	111	114	113	116	113	117	110	113	105	109	100	104	93	97
e, percent (S-basis):														
LT	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi:														
Primary	10.3													
Secondary	10.0													
E_c, 10^3 ksi:														
Primary	10.6													
Secondary	10.3													
G, 10^3 ksi	...													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	...													

a These values, except in the ST direction, have been adjusted to represent the average properties across the whole section, including the 1-1/2 percent per side nominal cladding thickness.

b Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

c Bearing values are “dry pin” values per Section 1.4.7.1. See Table 3.1.2.1.1

Table 3.7.6.0(c_4). Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Plate—Continued

Specification	AMS-QQ-A-250/13													
Form	Plate													
Temper	T62[a]													
Thickness, in.	0.250-0.499		0.500-1.000[b]		1.001-2.000[b]		2.001-2.500[b]		2.501-3.000[b]		3.001-3.500[b]		3.501-4.000[b]	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:														
F_{tu}, ksi:														
L	72	73	72	74	72	73	71	72	67	69	66	68	62	64
LT	75	77	76	78	75	77	74	76	70	72	69	71	65	67
ST	...	...	...	...	...	...	70[c]	71[c]	66[c]	68[c]	65[c]	67[c]	61[c]	63[c]
F_{ty}, ksi:														
L	63	65	64	66	62	64	58	60	54	56	50	52	46	48
LT	65	67	66	68	65	67	62	64	59	61	56	58	52	54
ST	...	...	...	...	...	...	59[c]	61[c]	56[c]	58[c]	54[c]	55[c]	50[c]	52[c]
F_{cy}, ksi:														
L	68	70	68	70	66	68	62	63	57	59	53	55	48	50
LT	68	70	69	71	66	68	62	65	59	61	55	57	50	52
ST	...	...	...	...	...	...	63	65	60	62	57	59	53	55
F_{su}, ksi	42	43	42	44	42	44	43	44	41	42	40	42	38	39
F_{bru}[d], ksi:														
(e/D = 1.5)	113	116	114	117	113	116	111	114	105	108	104	107	98	101
(e/D = 2.0)	139	143	141	145	139	143	137	141	130	134	128	132	121	124
F_{bry}[d], ksi:														
(e/D = 1.5)	94	97	97	100	97	100	95	98	90	94	86	89	80	84
(e/D = 2.0)	111	114	113	116	113	117	110	113	105	109	100	104	93	97
e, percent (S-basis):														
LT	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi:														
Primary	10.3													
Secondary	10.0													
E_c, 10^3 ksi:														
Primary	10.6													
Secondary	10.3													
G, 10^3 ksi	3.9													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	...													

a Design allowables were based upon data obtained from testing samples of plate, supplied in the O or F temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.
b These values, except in the ST direction, have been adjusted to represent the average properties across the whole section.
c Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).
d Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.6.0(c_5). Design Mechanical and Physical Properties of Clad 7075 Aluminum Alloy Sheet and Plate—Continued

Specification	AMS-QQ-A-250/25				
Form	Sheet			Plate	
Temper	T76			T7651	
Thickness, in,.	0.040-0.062	0.063-0.187	0.188-0.249	0.250-0.499	0.500-1.000[a]
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	66	67	69	68	68
LT	67	68	70	69	68
F_{ty}, ksi:					
L	56	57	59	58	57
LT	56	57	59	58	57
F_{cy}, ksi:					
L	55	56	58	57	56
LT	59	60	62	60	59
F_{su}, ksi	41	40	40	40	40
F_{bru}[b], ksi:					
(e/D = 1.5)	103	104	107	105	103
(e/D = 2.0)	133	135	139	133	131
F_{bry}[b], ksi:					
(e/D = 1.5)	80	81	84	87	87
(e/D = 2.0)	92	94	97	104	103
e, percent:					
LT	8	8	8	8	6
E, 10^3 ksi:					
Primary	10.3		10.3	10.3	
Secondary	9.8		10.0	10.0	
E_c, 10^3 ksi:					
Primary	10.5		10.5	10.6	
Secondary	10.0		10.2	10.3	
G, 10^3 ksi	...		...	...	
μ	0.33		0.33	0.33	
Physical Properties:					
ω, lb/in.^{3}	0.101				
C, K, and α	...				

a These values have been adjusted to represent the average properties across the whole section, including the 1-1/2 percent per side nominal cladding thickness.
b Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.6.0(d). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Bar, Rod, and Shapes: Rolled, Drawn, or Cold-Finished

Specification	AMS 4122, AMS 4123, AMS 4186, AMS 4187, and AMS-QQ-A-225/9								AMS 4124 and AMS-QQ-A-225/9	
Form	Bar, rod, and shapes: rolled, drawn, or cold-finished									
Temper	T6, T651, and T62[a]								T73[b] or T7351	
Thickness[c], in.	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000		0.375-2.000	2.001-3.000
Basis	A	B	A	B	A	B	A	B	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	77	79	77	79	77	79	77	79	68	68
LT	77[d]	79[d]	75[d]	77[d]	72[d]	74[d]	69[d]	71[d]	...	65[e]
F_{ty}, ksi:										
L	66	68	66	68	66	68	66	68	56	56
LT	66[d]	68[d]	66[d]	68[d]	63[d]	65[d]	60[d]	62[d]	...	52[e]
F_{cy}, ksi:										
L	64	66	64	66	64	66	64	66	54	54
LT	...	...	...	...	...	...	...	...	...	55[e]
F_{su}, ksi	46	47	46	47	46	47	46	47	42	40
F_{bru}[f], ksi:										
(e/D = 1.5)	100	103	100	103	100	103	100	103	101	101
(e/D = 2.0)	123	126	123	126	123	126	123	126	131	131
F_{bry}[f], ksi:										
(e/D = 1.5)	86	88	86	88	86	88	86	88	81	81
(e/D = 2.0)	92	95	92	95	92	95	92	95	100	100
e, percent (S-basis):										
L	7	...	7	...	7	...	7	...	10	10
E, 10^3 ksi	10.3									
E_c, 10^3 ksi	10.5									
G, 10^3 ksi	3.9									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.101									
C, K, and α	See Figure 3.7.6.0									

a Design allowables were based upon data obtained from testing of T6 and T651 material and from samples of material, supplied in the O or F temper, which were heat treated to T62 temper to demonstrate response to heat treatment by suppliers.
b Design allowables were based upon data obtained from testing T73 and T7351 temper material and from testing samples of material, supplied in the O or F temper, which were heat treated to T73 temper to demonstrate response to heat treatment by suppliers.
c For rounds (rod) maximum diameter is 4 inches; for square bar, maximum size is 3½ inches; for rectangular bar, maximum thickness is 3 inches with corresponding width of 6 inches; for rectangular bar less than 3 inches in thickness, maximum width is 10 inches.
d Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).
ST grain direction.
e ST grain direction.
f Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.6.0(e_1). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Die Forging

Specification	AMS 4126, MIL-A-22771, and QQ-A-367							MIL-A-22771 and QQ-A-367						
Form	Die forging													
Temper	T6[a]							T652						
Thickness[b], in.	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000
Basis	A	B	A	B	A	B	S	A	B	A	B	A	B	S
Mechanical Properties:														
F_{tu}, ksi:														
L	75	78	74	77	74	76	73	75	78	74	77	74	76	73
T[c]	71[d]	...	71[d]	...	70[d]	...	70	71[d]	...	71[d]	...	70[d]	...	70
F_{ty}, ksi:														
L	64	67	63	66	63	65	62	64	67	63	66	63	65	62
T[c]	61[d]	...	61[d]	...	60[d]	...	60	60[d]	...	60[d]	...	59[d]	...	59
F_{cy}, ksi:														
L	67	70	66	69	66	68	65	64	67	63	66	63	65	62
ST	64	68	64	67	63	66	63	65	69	65	68	64	67	64
F_{su}, ksi	43	45	43	44	42	43	42	43	45	43	44	42	43	42
F_{bru}[e], ksi:														
(e/D = 1.5)	105	109	104	108	104	106	102	105	109	104	108	104	106	102
(e/D = 2.0)	135	140	133	138	133	136	131	135	140	133	138	133	136	131
F_{bry}[e], ksi:														
(e/D = 1.5)	83	87	82	86	82	84	81	83	87	82	86	82	84	81
(e/D = 2.0)	96	100	94	99	94	97	93	96	100	94	99	94	97	93
e, percent (S-basis):														
L	7	...	7	...	7	...	7	7	...	7	...	7	...	7
T[c]	3	...	3	...	3	...	2	3	...	3	...	3	...	2
E, 10^3 ksi	10.0													
E_c, 10^3 ksi	10.4													
G, 10^3 ksi	3.8													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.7.6.0													

a When die forgings are machined before heat treatment, the mechanical properties are applicable provided the as-forged thickness is not greater than twice the thickness at time of heat treatment.
b Thickness at the time of heat treatment.
c T indicates any grain direction not within ±15° of being parallel to the forging flow lines. F_{cy}(T) values are based upon short transverse (ST) test data.
d Specification value. T tensile properties are presented on an S basis only.
e Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.6.0(e_2). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Die Forging—Continued

Specification	AMS 4141, AMS-A-22771, and AMS-QQ-A-367								AMS 4141		AMS 4147, AMS-A-22771, and AMS-QQ-A-367		
Form	Die forging												
Temper	T73[a,b]										T7352		
Thickness[c], in.	≤1.000		1.001-2.000		2.001-3.000		3.001-4.000		4.001-5.000	5.001-6.000	≤3.000		3.001-4.000
Basis	A	B	A	B	A	B	A	B	S	S	A	B	S
Mechanical Properties[d]:													
F_{tu}, ksi:													
L	66	71	66	71	66	69	64	69	62	61	66	69	64
T[e]	62[f]	...	62[f]	...	62[f]	...	61[f]	...	59	58	62[f]	...	61
F_{ty}, ksi:													
L	56	61	56	59	56	59	55	59	53	51	56	59	53
T[e]	53[f]	...	53[f]	...	53[f]	...	52[f]	...	51	50	51[f]	...	49
F_{cy}, ksi:													
L	58	63	58	61	58	61	57	61	...	...	56	59	53
T[e]	55	60	55	59	55	59	54	58	...	...	55	60	53
F_{su}, ksi	39	42	39	42	39	41	38	41	...	...	39	41	38
F_{bru}[g], ksi:													
(e/D = 1.5)	96	103	96	103	96	100	93	100	...	...	96	100	93
(e/D = 2.0)	125	135	125	135	125	131	122	131	...	...	125	131	122
F_{bry}[g], ksi:													
(e/D = 1.5)	78	85	78	83	78	83	77	83	...	...	78	83	74
(e/D = 2.0)	90	98	90	94	90	94	88	94	...	...	90	94	85
e, percent (S-basis):													
L	7	...	7	...	7	...	7	...	7	6	7	...	7
T[e]	3	...	3	...	3	...	2	...	2	2	3	...	2
E, 10^3 ksi	10.0												
E_c, 10^3 ksi	10.4												
G, 10^3 ksi	3.8												
μ	0.33												
Physical Properties:													
ω, lb/in.^{3}	0.101												
C, K, and α	See Figure 3.7.6.0												

a When die forgings are machined before heat treatment, the mechanical properties are applicable, provided the as-forged thickness is not greater than twice the thickness at the time of heat treatment.
b Design allowables were based upon data obtained from testing die forgings, heat treated by suppliers, and supplied in T73 temper.
c Thickness at the time of heat treatment.
d Most of the A tensile values are higher than specification values; consequently, the A values shown are specification values.
e When MIL-A-22771 or QQ-A-367 apply, T indicates any grain direction not within ±15° of being parallel to the forging flow lines. F_{cy} (T) values are based upon short transverse (ST) test data. When AMS 4141 applies, T indicates any grain direction within ±15° of being perpendicular to the forging flow lines.
f Specification value. T tensile properties are presented on an S basis only.
g Bearing values are “dry pin” values per Section 1.4.7.1.

Table 3.7.6.0(f_1). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Hand Forging

Specification	AMS 4126, AMS-A-22771, and AMS-QQ-A-367					AMS-A-22771 and AMS-QQ-A-367				
Form	Hand forging									
Temper	T6[a]					T652				
Thickness, in.	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	74	73	71	69	68	74	73	71	69	68
LT	73	71	70	68	66	73	71	70	68	66
ST	...	69[b]	68[b]	66[b]	65[b]	...	69[b]	68[b]	66[b]	65[b]
F_{ty}, ksi:										
L	63	61	60	58	56	63	61	60	58	56
LT	61	59	58	56	55	61	59	58	56	55
ST	...	58[b]	57[b]	56[b]	55[b]	...	57[b]	56[b]	55[b]	54[b]
F_{cy}, ksi:										
L	63	61	...	...	...	63	61	...	...	...
LT	61	59	...	...	...	61	59	...	...	...
F_{su}, ksi	44	44	43	41	41	44	44	43	41	41
F_{bru}, ksi:										
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...
F_{bry}, ksi:										
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...
e, percent:										
L	9	9	8	7	6	9	9	8	7	6
LT	4	4	3	3	3	4	4	3	3	3
ST	...	3	2	2	2	...	2	1	1	1
E, 10^3 ksi	10.0									
E_c, 10^3 ksi	10.4									
G, 10^3 ksi	3.8									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	0.101									
C, K, and α	See Figure 3.7.6.0									

a When hand forgings are machined before heat treatment, the section thickness at time of heat treatment shall determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness of the alloy as shown in the table. The maximum cross-sectional area of hand forgings is 256 sq in.

b Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).

Table 3.7.6.0(f_2). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Hand Forging—Continued

Specification	AMS-A-22771 and AMS-QQ-A-367					AMS 4147, AMS-A-22771, and AMS-QQ-A-367					
Form	Hand forging										
Temper	T73[a]					T7352					
Thickness, in.	≤2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000	≤2.000	2.001-3.000	3.001-4.000		4.001-5.000	5.001-6.000
Basis	S	S	S	S	S	S	S	A	B	S	S
Mechanical Properties:											
F_{tu}, ksi:											
L	66	66	64	62	61	66	66	64	67	62	61
LT	64	64	63	61	59	64	64	63	66	61	59
ST	...	61	60	58	57	...	61	60	63	58	57
F_{ty}, ksi:											
L	56	56	55	53	51	54	54	53	55	51	49
LT	54	54	53	51	50	52	52	50	53	48	46
ST	...	52	51	50	49	...	50	48	51	46	44
F_{cy}, ksi:											
L	56	56	...	...	...	55	55	52	55	49	46
LT	52	52	...	...	...	55	55	52	55	49	46
ST	...	...	...	...	...	55	55	53	56	51	49
F_{su}, ksi:											
L	39	39	...	...	...	39	39	38	40	37	36
LT	...	...	...	...	...	36	36	37	38	36	35
ST	...	...	...	...	...	38	38	37	39	36	35
F_{bru}[b], ksi:											
(e/D = 1.5)	...	...	...	...	...	86	88	89	93	86	84
(e/D = 2.0)	...	...	...	...	...	120	120	118	123	114	110
F_{bry}[b], ksi:											
(e/D = 1.5)	...	...	...	...	...	71	73	73	77	71	68
(e/D = 2.0)	...	...	...	...	...	90	90	87	92	83	80
e, percent (S-basis):											
L	7	7	7	7	6	7	7	7	...	7	6
LT	4	4	3	3	3	4	4	3	...	3	3
ST	...	3	2	2	2	...	3	2	...	2	2
E, 10^3 ksi	10.2										
E_c, 10^3 ksi	10.4										
G, 10^3 ksi	3.8										
μ	0.33										
Physical Properties:											
ω, lb/in.^{3}	0.101										
C, K, and α	See Figure 3.7.6.0										

a When hand forgings are machined before heat treatment, the section thickness at time of heat treatment shall determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table. The maximum cross-sectional area of hand forgings is 256 sq. in.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.6.0(g_1). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Extrusion

Specification	AMS-QQ-A-200/11														
Form	Extrusion (rod, bar, and shapes)														
Temper	T6, T6510, T6511, and T62[a]														
Cross-Sectional Area, in.^{2}	≤20												>20, ≤32	≤32	
Thickness, in.[b]	≤0.249		0.250-0.499		0.500-0.749		0.750-1.499		1.500-2.999		3.000-4.499			4.500-5.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	S	A	B
Mechanical Properties:															
F_{tu}, ksi:															
L	78	82	81	85	81	85	81	85	81	85	81	84	78	78	81
LT	75	79	78	82	77	81	75	79	71	75	67	69	64	63	65
ST	...	...	...	...	...	...	...	...	67[c]	71[c]	67[c]	69[c]	64[c]	63[c]	65[c]
F_{ty}, ksi:															
L	70	74	73	77	72	76	72	76	72	76	71	74	70	68	71
LT	66	70	69	72	67	71	65	69	61	65	56	59	55	52	55
ST	...	...	...	...	...	...	...	...	56[c]	59[c]	55[c]	58[c]	55[c]	52[c]	55[c]
F_{cy}, ksi:															
L	70	74	73	77	72	76	72	76	72	76	71	74	70	68	71
LT	72	76	74	78	73	77	71	75	67	71	62	64	61	57	60
ST	...	...	...	...	...	...	...	...	62	66	62	64	61	57	60
F_{su}, ksi	41	44	43	45	43	45	43	45	42	44	40	42	39	38	40
F_{bru}[d], ksi:															
(e/D = 1.5)	111	117	115	121	115	120	113	119	110	115	106	110	102	101	105
(e/D = 2.0)	140	148	146	153	145	152	144	151	141	148	137	142	132	131	136
F_{bry}[d], ksi:															
(e/D = 1.5)	92	97	96	101	94	99	93	98	89	94	84	88	83	79	83
(e/D = 2.0)	108	114	113	119	111	117	110	116	106	112	101	105	100	95	100
e, percent (S-basis):															
L	7	...	7	...	7	...	7	...	7	...	7	...	6	6	...
E, 10^3 ksi	10.4														
E_c, 10^3 ksi	10.7														
G, 10^3 ksi	4.0														
μ	0.33														
Physical Properties:															
ω, lb/in.^{3}	0.101														
C, K, and α	See Figure 3.7.6.0														

a Design allowables were based upon data obtained from testing T6, T6510, and T6511 temper extrusions and from testing samples of extrusion supplied in the O or F temper, which were heat treated to T62 temper to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.
b The mechanical properties are to be based upon the thickness at the time of quench.
c Caution: This specific alloy, temper, and product form exhibits poor stress-corrosion cracking resistance in this grain direction. It corresponds to an SCC resistance rating of D, as indicated in Table 3.1.2.3.1(a).
d Bearing values are "dry pin" values per Section 1.4.7.1.

Supersedes page 3-361 of MIL-HDBK-5H

Table 3.7.6.0(g_2). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Extrusion—Continued

Specification	AMS-QQ-A-200/11													
Form	Extrusion (rod, bars, and shapes)													
Temper	T73[a], T73510, T73511													
Cross-Sectional Area, in.^{2}	≤20		≤25								≤20		>20, ≤32	
Thickness, in.[b]	0.062-0.249		0.250-0.499		0.500-0.749		0.750-1.499		1.500-2.999		3.000-4.499		3.000-4.499	
Basis	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:														
F_{tu}, ksi:														
L	68[c]	72	70[c]	74	70[c]	73	70[c]	73	69[c]	74	68[c]	71	65[c]	70
LT	66	70	68	72	67	70	66	69	62	67	58	61	56	60
F_{ty}, ksi:														
L	58	61	60	63	60	63	60	63	59[c]	65	57[c]	62	55[c]	60
LT	56	59	57	60	57	60	56	58	51	56	46	50	44	48
F_{cy}, ksi:														
L	58	61	60	63	60	63	60	63	59	65	57	62	55	60
LT	59	62	60	63	60	63	58	61	54	59	49	53	47	51
F_{su}, ksi	37	39	38	40	38	39	38	39	37	40	37	38	35	38
F_{bru}[d], ksi:														
(e/D = 1.5)	101	107	104	110	103	108	103	107	99	106	95	99	91	98
(e/D = 2.0)	129	137	133	141	133	139	132	138	128	138	124	130	119	128
F_{bry}[d], ksi:														
(e/D = 1.5)	82	86	84	89	84	88	83	87	79	87	72	79	70	76
(e/D = 2.0)	97	102	100	105	100	105	98	103	93	103	86	94	83	91
e, percent (S-basis):														
L	7	...	8	...	8	...	8	...	8	...	7	...	7	...
E, 10^3 ksi	10.4													
E_c, 10^3 ksi	10.7													
G, 10^3 ksi	4.0													
μ	0.33													
Physical Properties:														
ω, lb/in.^{3}	0.101													
C, K, and α	See Figure 3.7.6.0													

a Design allowables were based upon data obtained from testing T7351X temper extrusions and from testing samples of extrusions supplied in the O or F temper, which were heat treated to T73 temper to demonstrate response to treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper.
b The mechanical properties are to be based upon the thickness at the time of quench.
c S-basis. See Table 3.7.6.0(g_3) for the rounded T_{99} values.
d Bearing values are “dry pin” values per Section 1.4.7.1.

Table 3.7.6.0(g_3). Rounded T_{99} Values for Tensile Yield and Ultimate Strength for 7075-T73, T73510, and T73511 Extrusion

Cross-Sectional Area, in.^{2} . .	≤20	≤25		≤20	>20, ≤32
Thickness, inch	0.062-0.249	0.250-1.499	1.500-2.999	3.000-4.499	3.000-4.499
Mechanical Properties:					
F_{tu}, ksi:					
L	69	71	72	69	68
F_{ty}, ksi:					
L	...	...	62	59	57

Table 3.7.6.0(g_4). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Extrusion—Continued

Specification	AMS-QQ-A-200/15						
Form	Extrusion (rod, bar, and shapes)						
Temper	T76, T76510, T76511						
Cross-Sectional Area, in.^{2}	≤20						
Thickness, in.[a]	0.062-0.249		0.250-0.499	0.500-0.749		0.750-1.000	
Basis	A	B	S	A	B	A	B
Mechanical Properties:							
F_{tu}, ksi:							
L	71	74	75	75	76	75	76
LT	68	71	72	71	73	70	71
F_{ty}, ksi:							
L	61	65	65	65	67	65	67
LT	57	61	61	60	62	59	61
F_{cy}, ksi:							
L	61	65	65	65	67	65	67
LT	62	66	66	65	67	64	66
F_{su}, ksi	38	40	41	41	42	40	41
F_{bru}[b], ksi:							
(e/D = 1.5)	103	107	109	109	110	109	110
(e/D = 2.0)	131	137	139	139	141	139	141
F_{bry}[b], ksi:							
(e/D = 1.5)	82	88	88	88	90	88	90
(e/D = 2.0)	98	104	104	104	107	104	107
e, percent (S-basis):							
L	7	...	7	7	...	7	...
E, 10^3 ksi	10.4						
E_c, 10^3 ksi	10.7						
G, 10^3 ksi	4.0						
μ	0.33						
Physical Properties:							
ω, lb/in.^{3}	0.101						
C, K, and α	See Figure 3.7.6.0						

a The mechanical properties are to be based upon the thickness at the time of quench.
b Bearing values are "dry pin" values per Section 1.4.7.1.

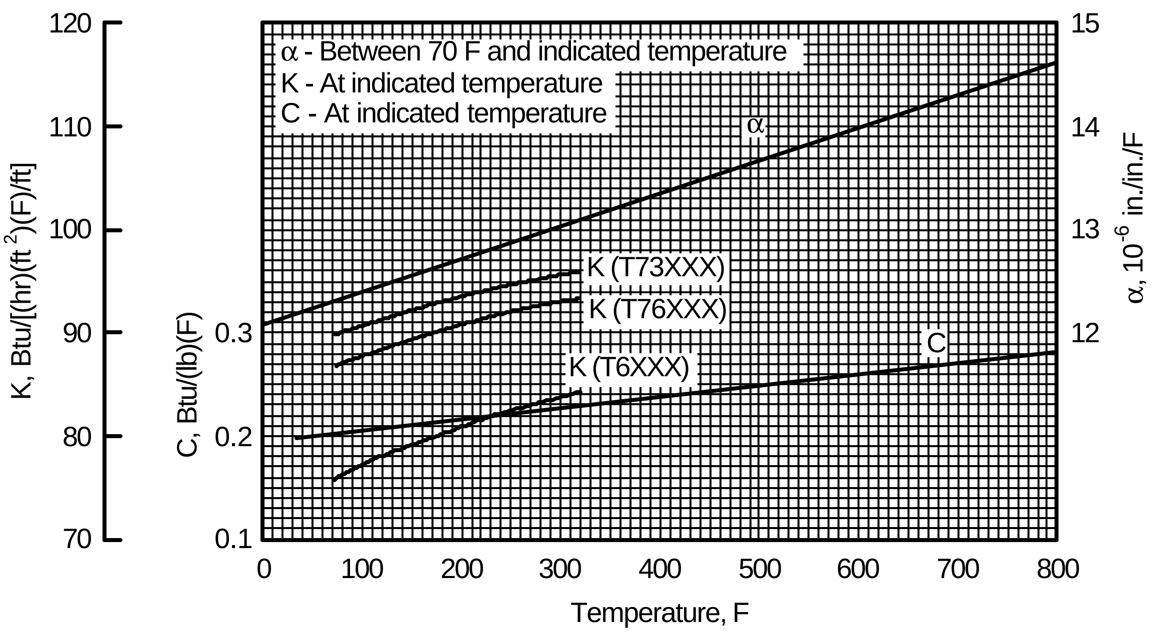

Figure 3.7.6.0. Effect of temperature on the physical properties of 7075 aluminum alloy.

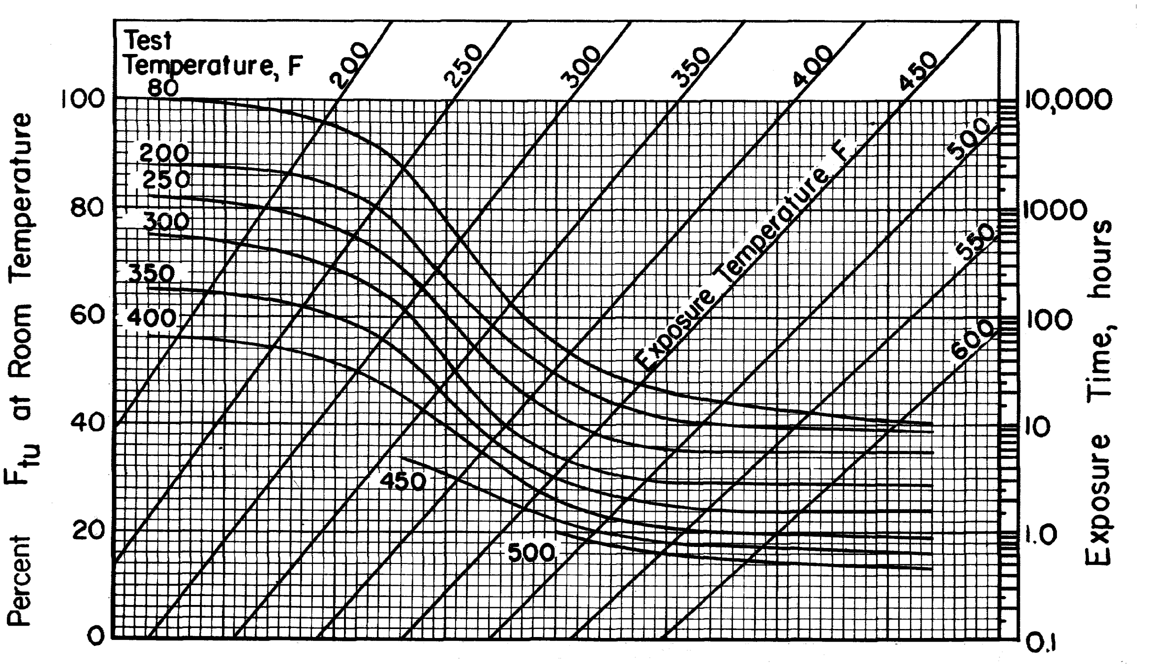

Figure 3.7.6.1.1(a). Effect of temperature on the tensile ultimate strength (F_{tu}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products). Note: Instructions for use of these curves are presented in Section 3.7.6.1.

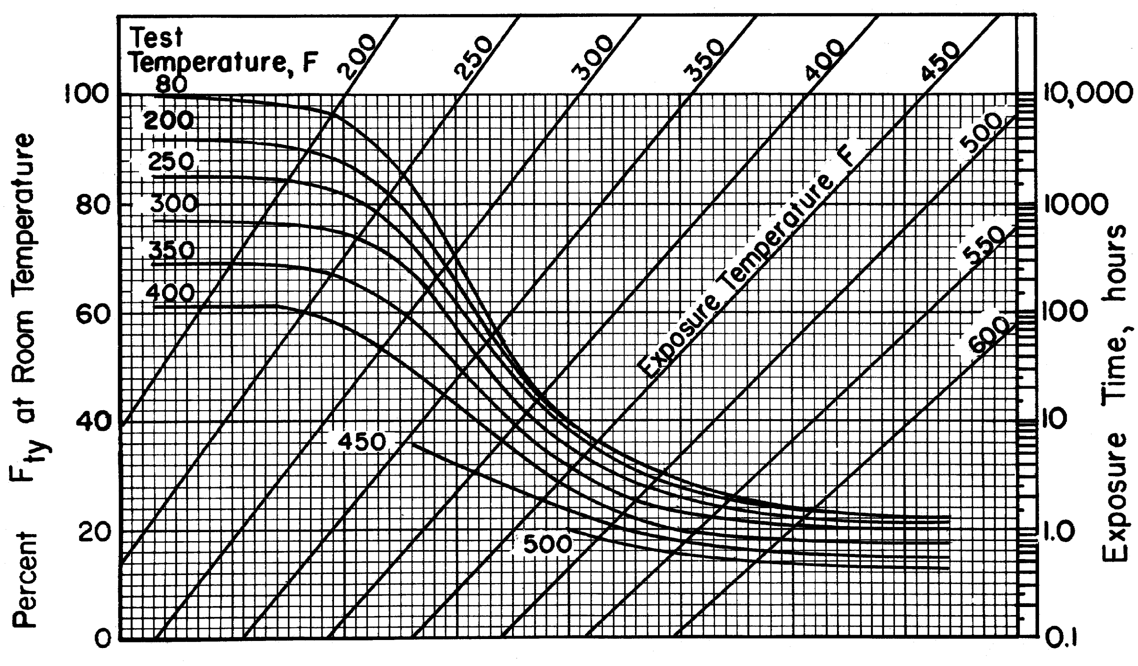

Figure 3.7.6.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products). Note: Instructions for use of these curves are presented in Section 3.7.6.1.

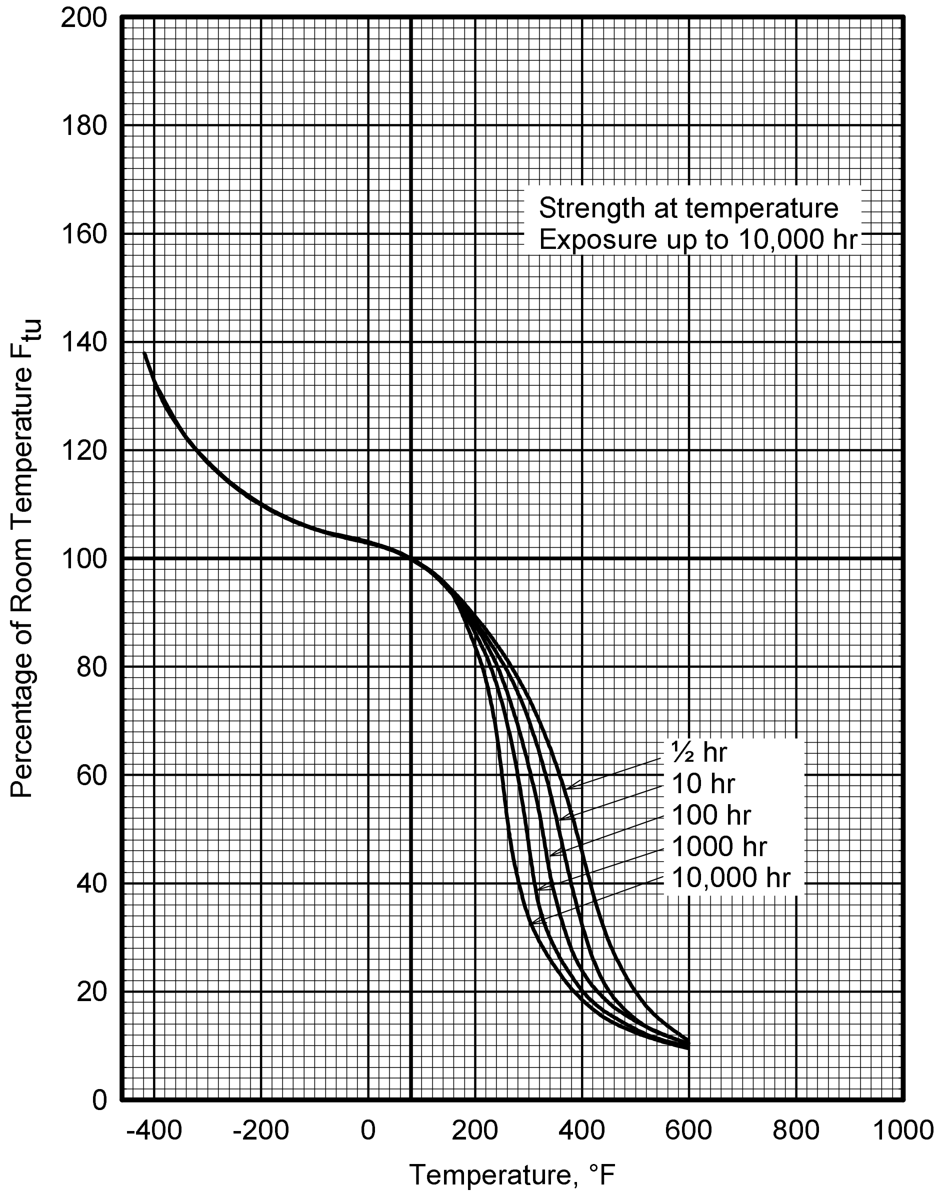

Figure 3.7.6.1.1(c). Effect of temperature on the tensile ultimate strength (F_{tu}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

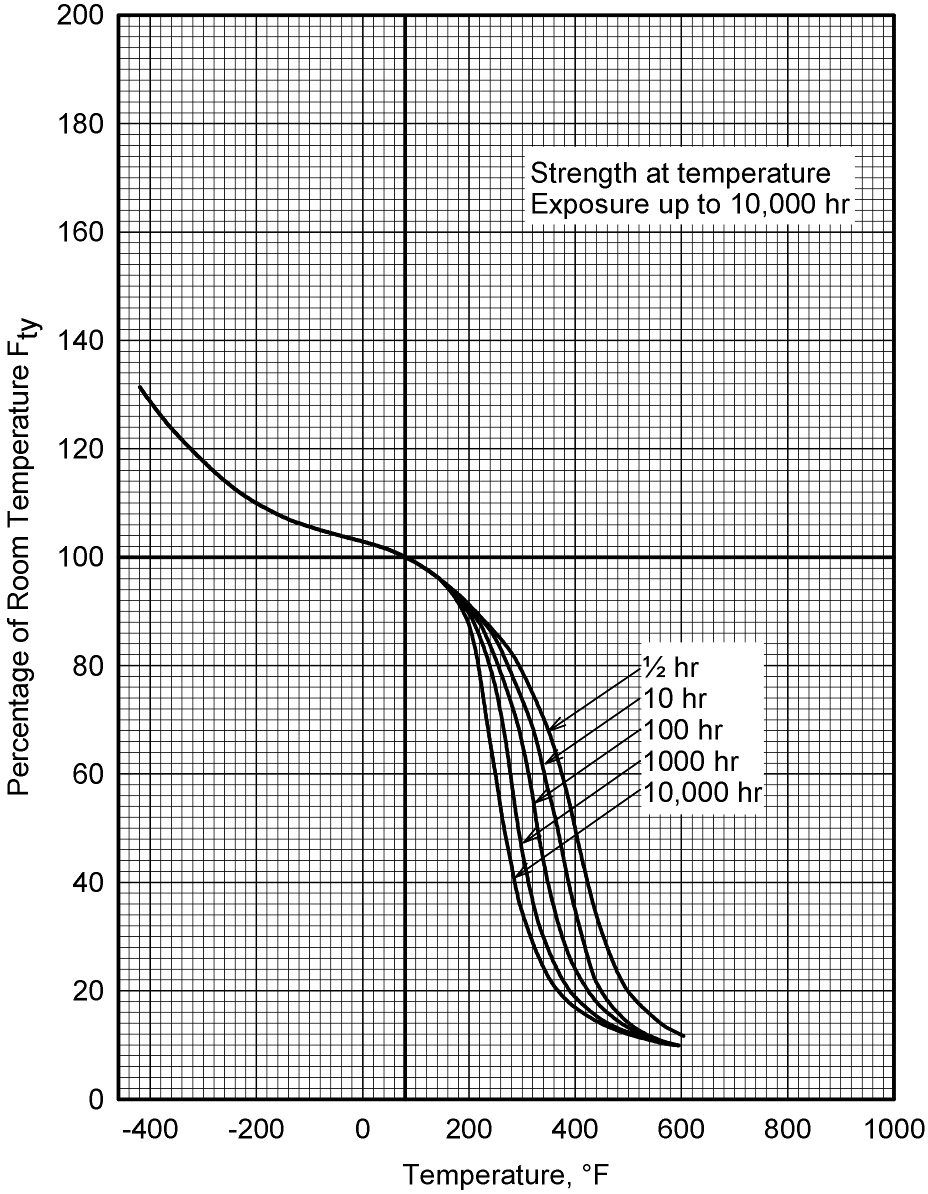

Figure 3.7.6.1.1(d). Effect of temperature on the tensile yield strength (F_{ty}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

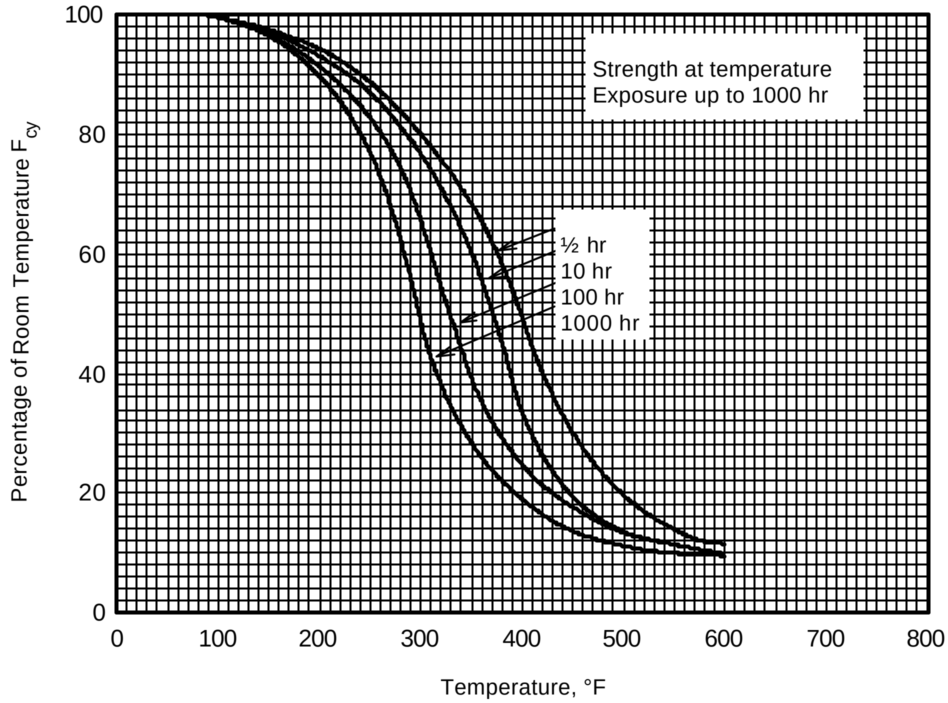

Figure 3.7.6.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

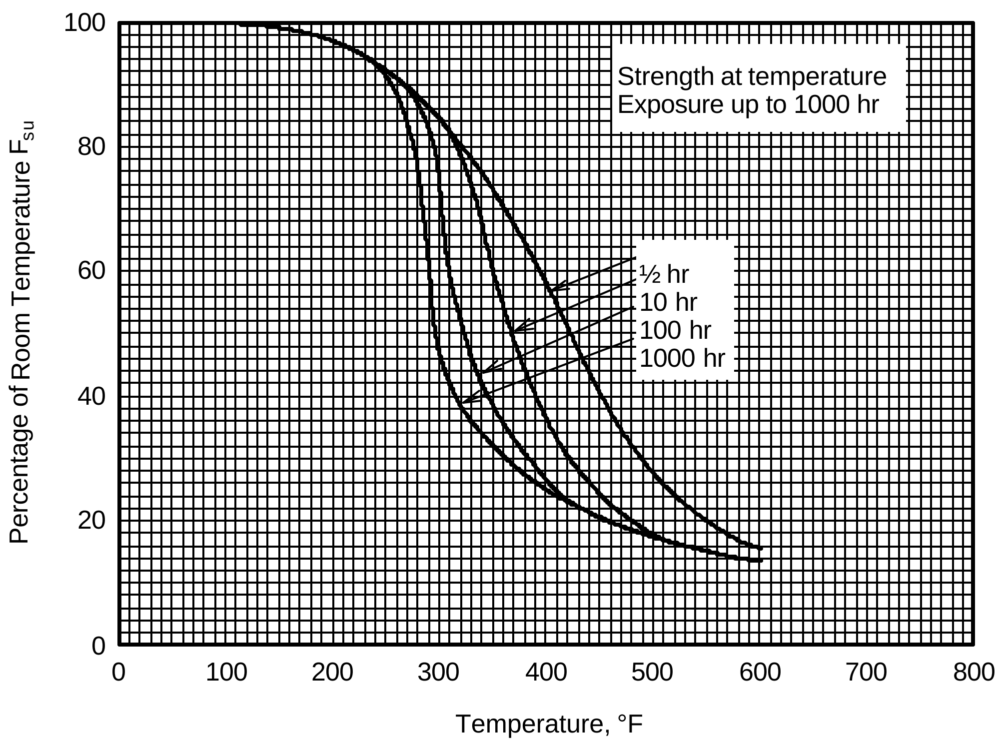

Figure 3.7.6.1.2(b). Effect of temperature on the shear ultimate strength (F_{su}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

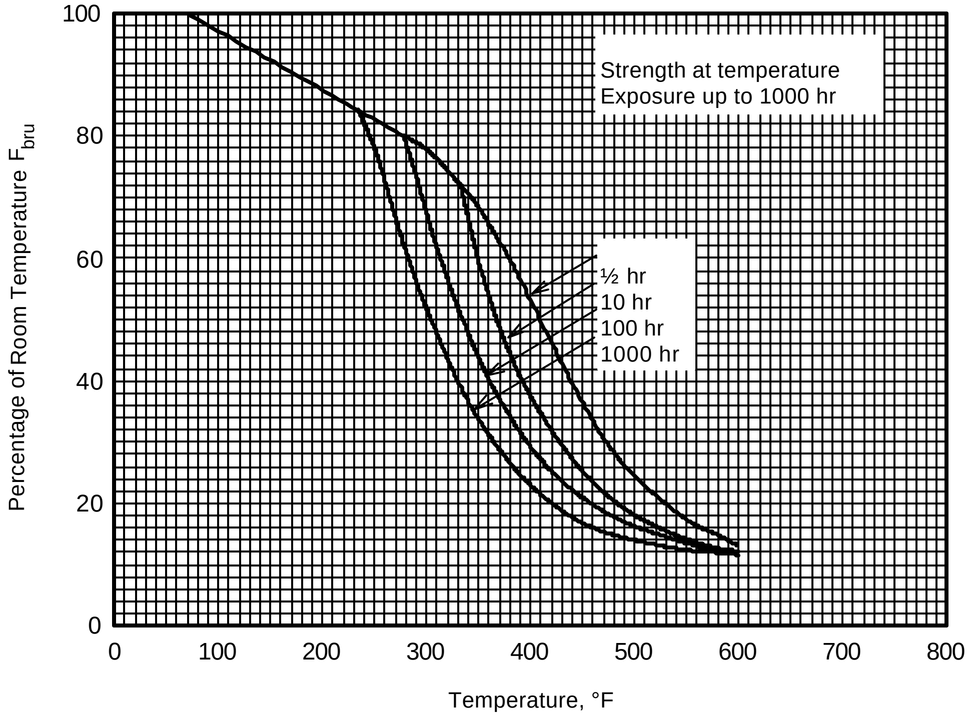

Figure 3.7.6.1.3(a). Effect of temperature on the bearing ultimate strength (F_{bru}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

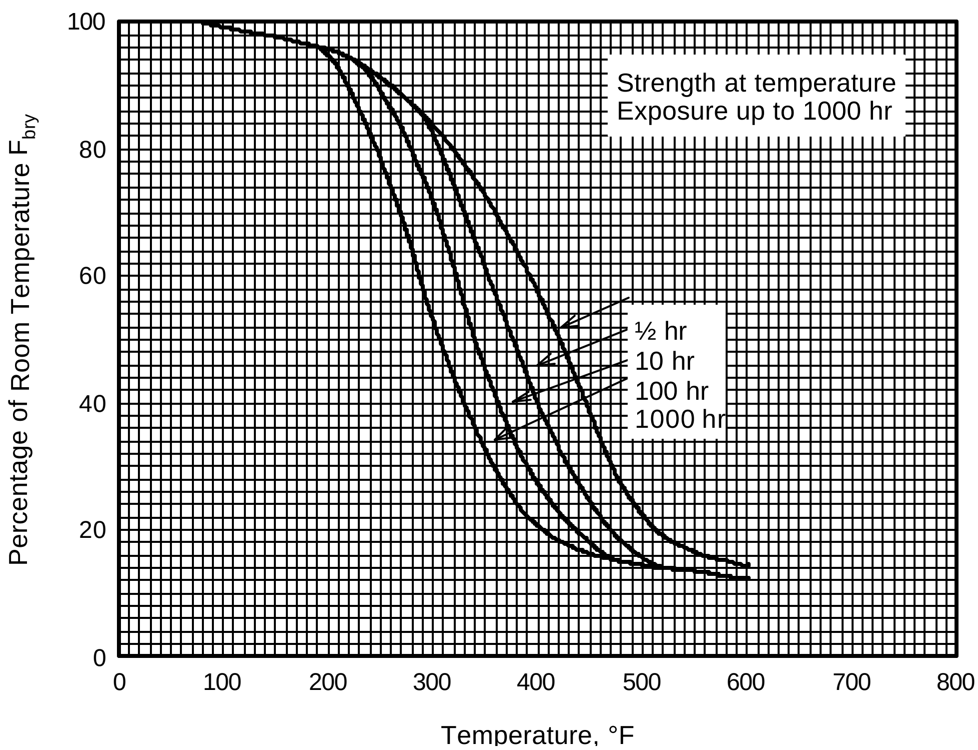

Figure 3.7.6.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

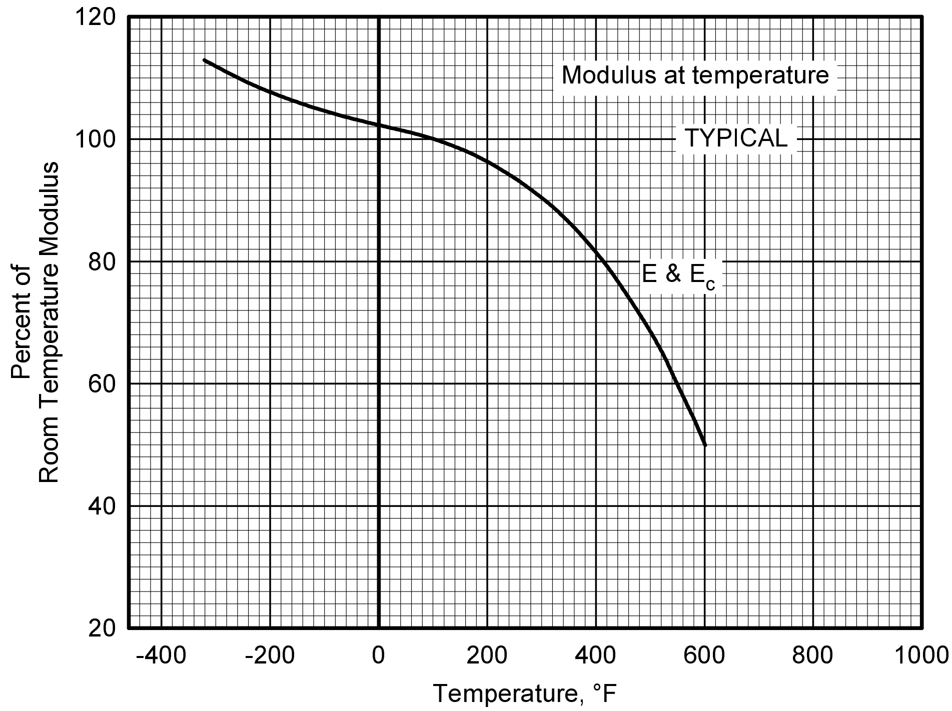

Figure 3.7.6.1.4. Effect of temperature on the tensile and compressive moduli (E and E_c) of 7075 aluminum alloy.

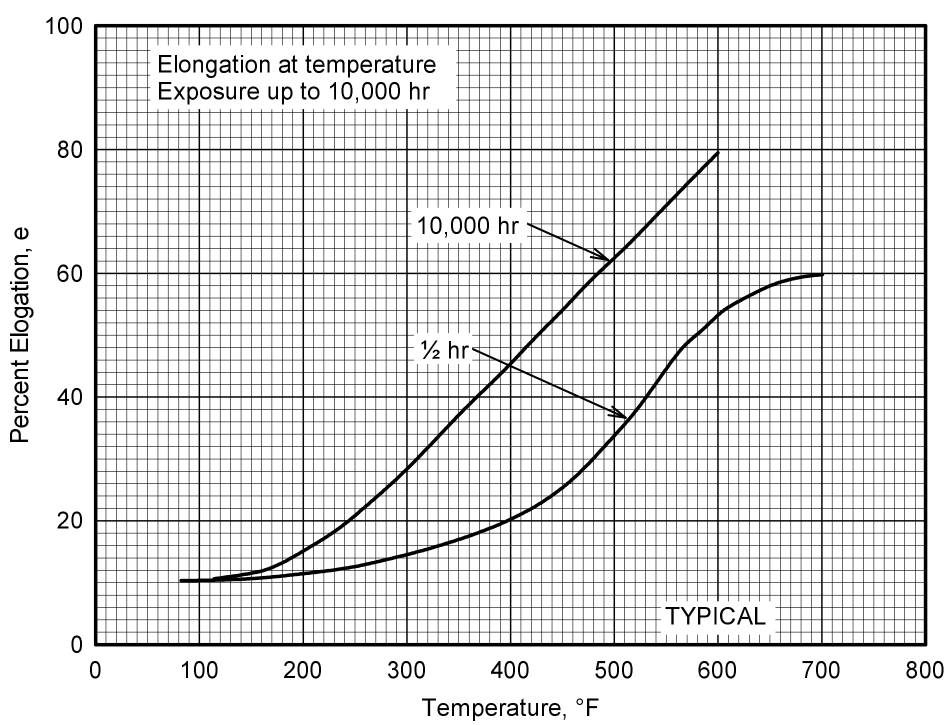

Figure 3.7.6.1.5(a). Effect of temperature on the elongation of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).

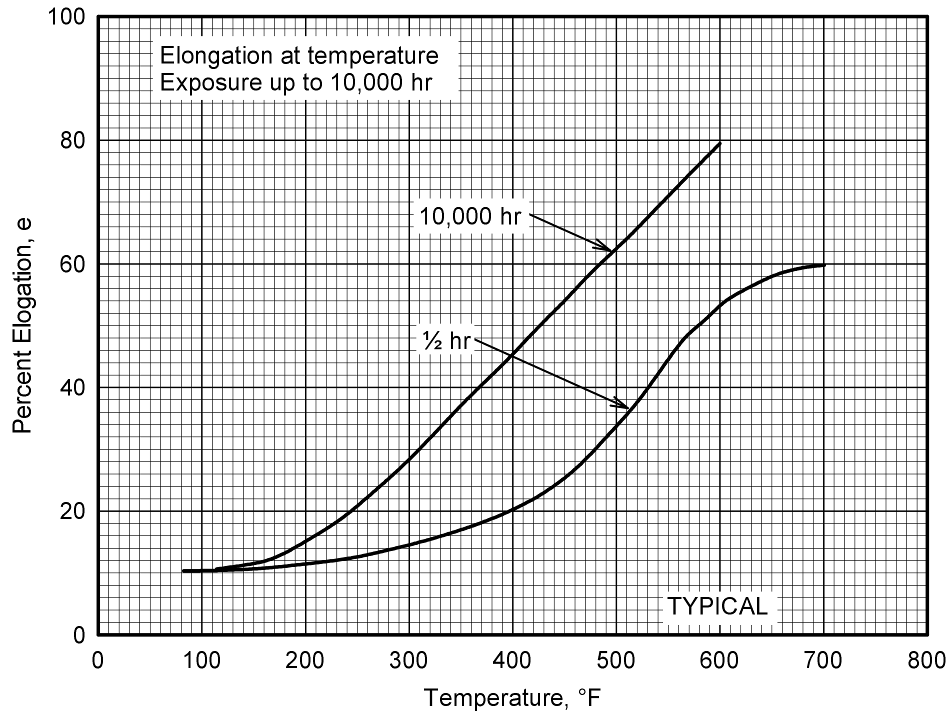

Figure 3.7.6.1.5(b). Effect of exposure at elevated temperatures on the elongation of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products except thick extrusions).

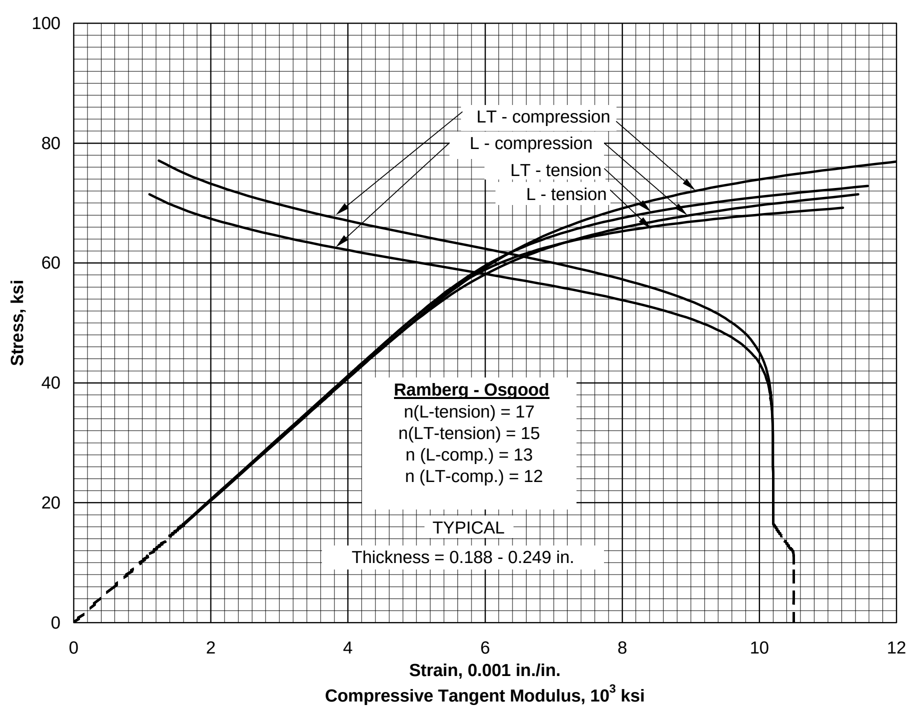

Figure 3.7.6.1.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at room temperature.

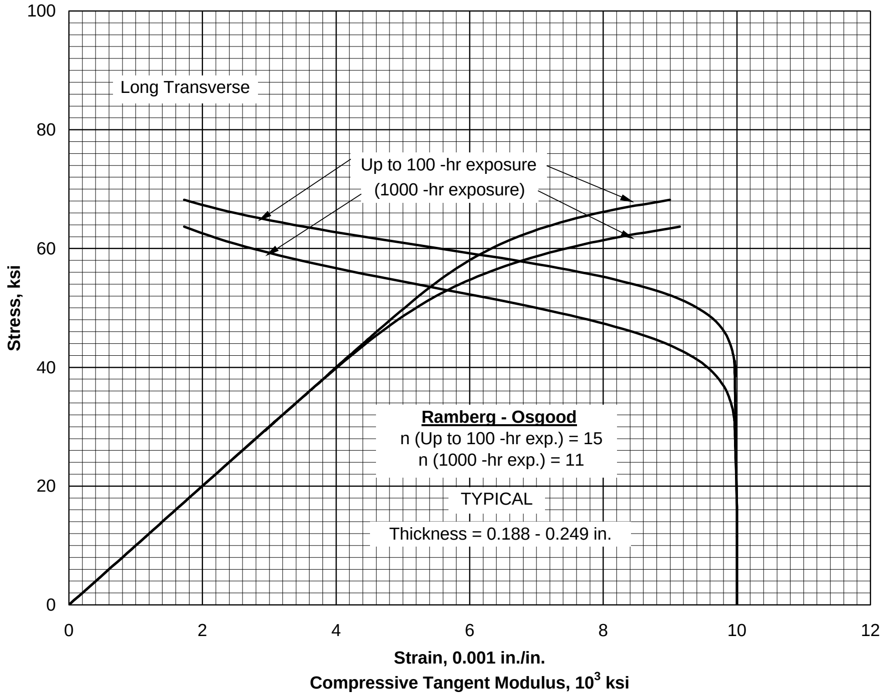

Figure 3.7.6.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 200EF.

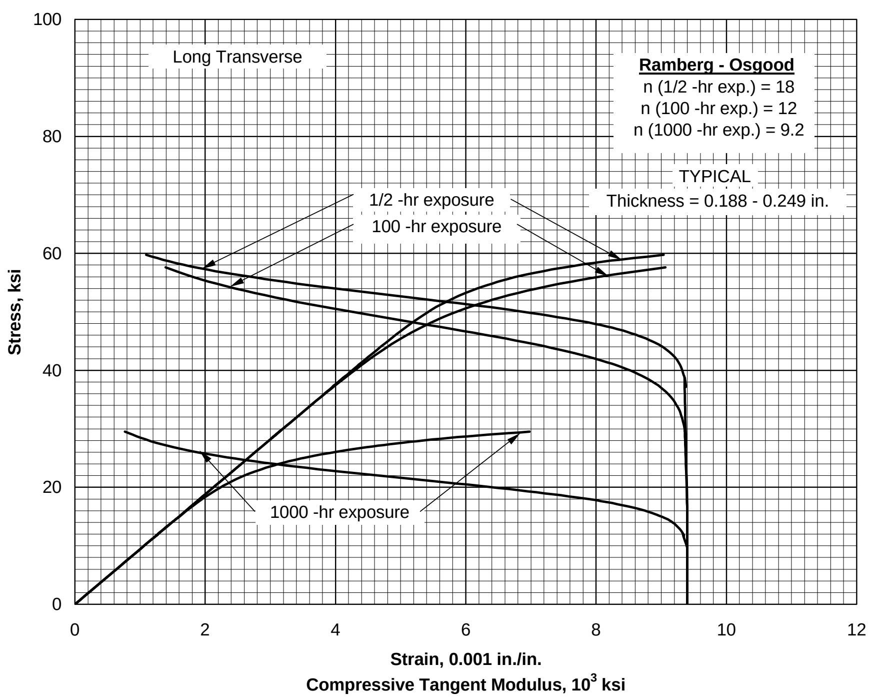

Figure 3.7.6.1.6(c). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 300EF.

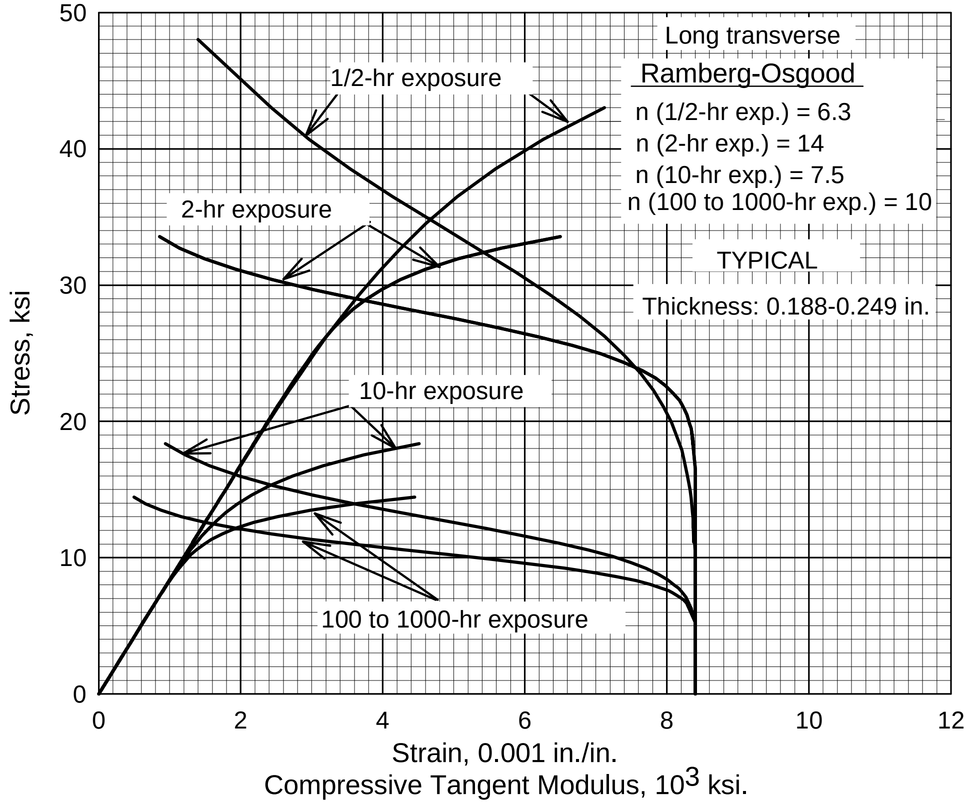

Figure 3.7.6.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 400EF.

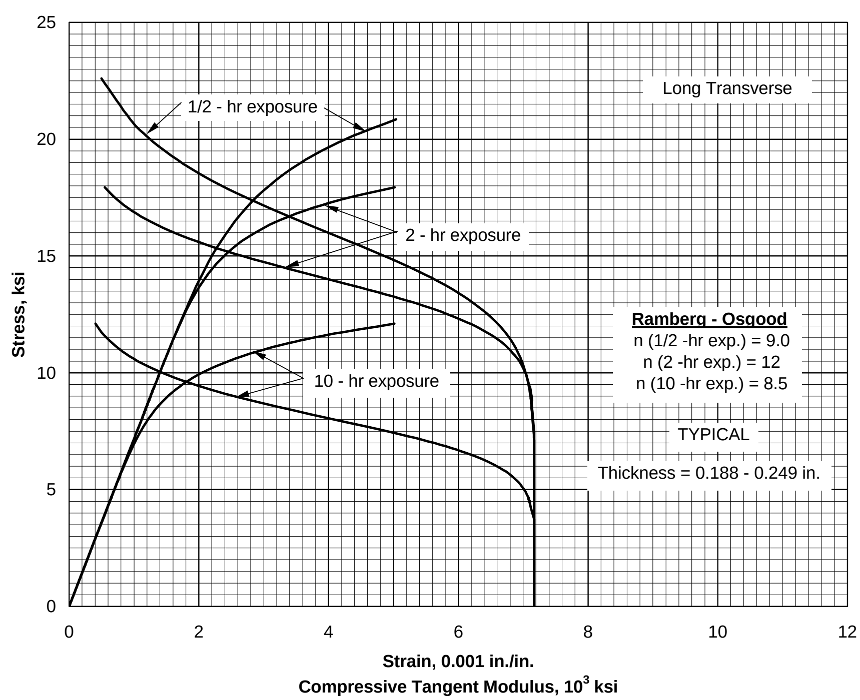

Figure 3.7.6.1.6(e). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 500EF.

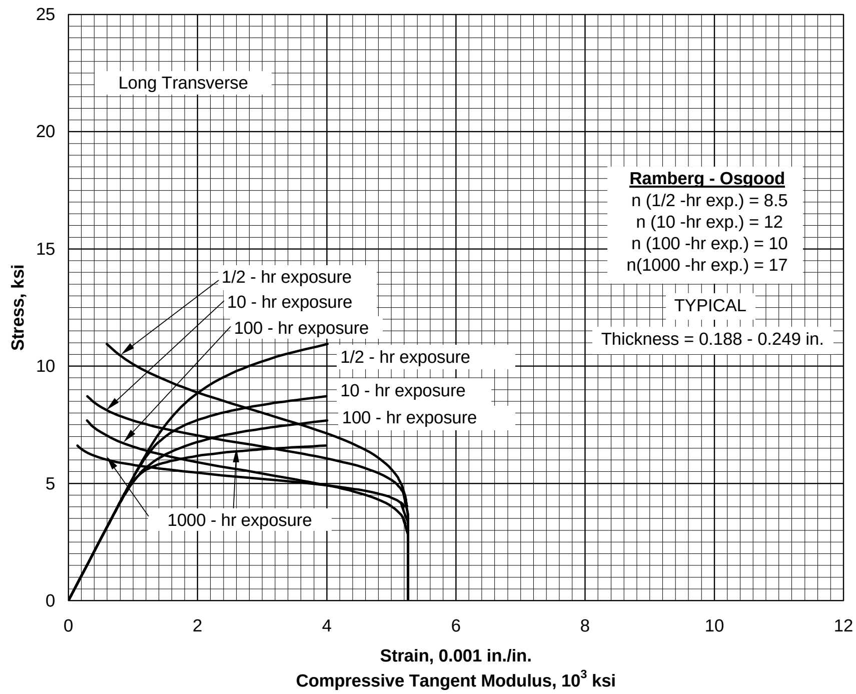

Figure 3.7.6.1.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7075-T6 aluminum alloy sheet at 600EF.

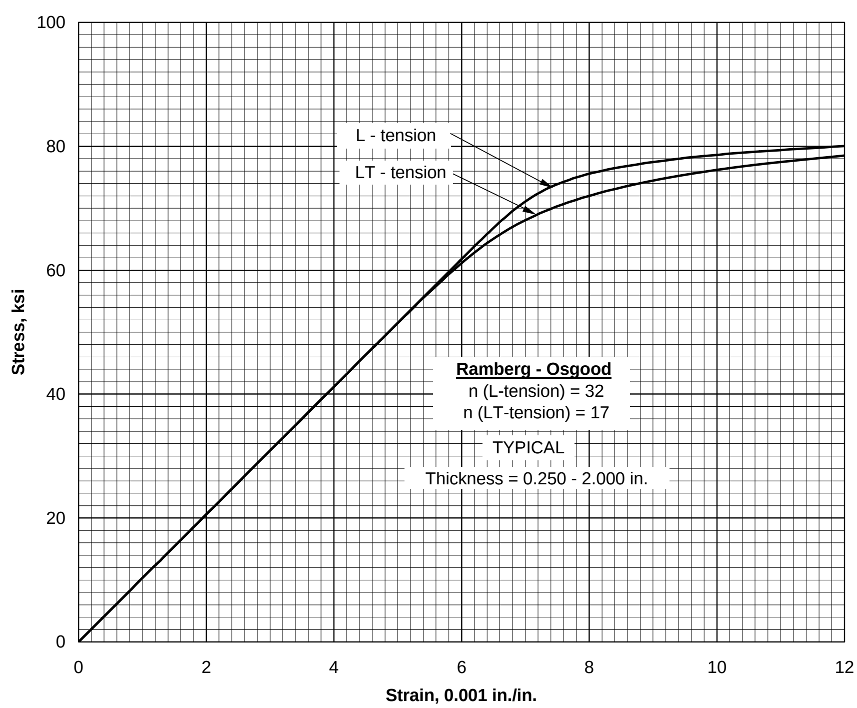

Figure 3.7.6.1.6(g). Typical tensile stress-strain curves for 7075-T651 aluminum alloy plate at room temperature.

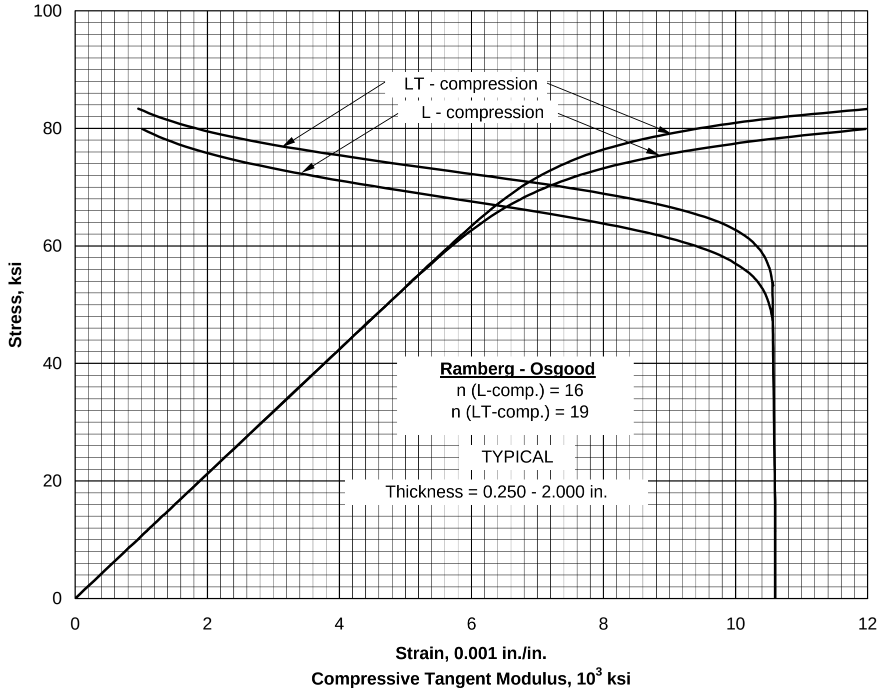

Figure 3.7.6.1.6(h). Typical compressive stress-strain and compressive tangent-modulus curves for 7075-T651 aluminum alloy plate at room temperature.

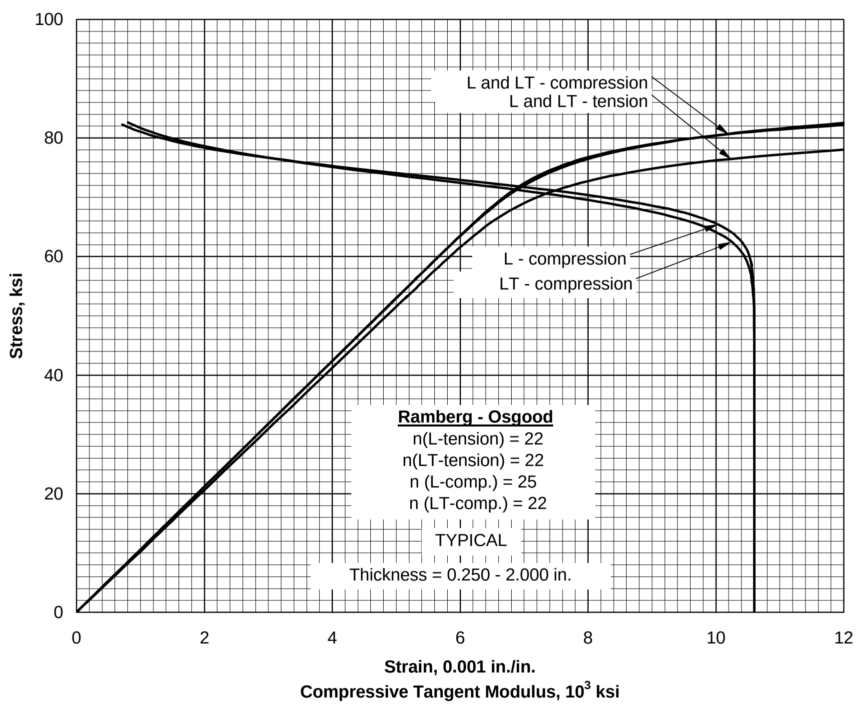

Figure 3.7.6.1.6(i). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T62 aluminum alloy plate at room temperature.

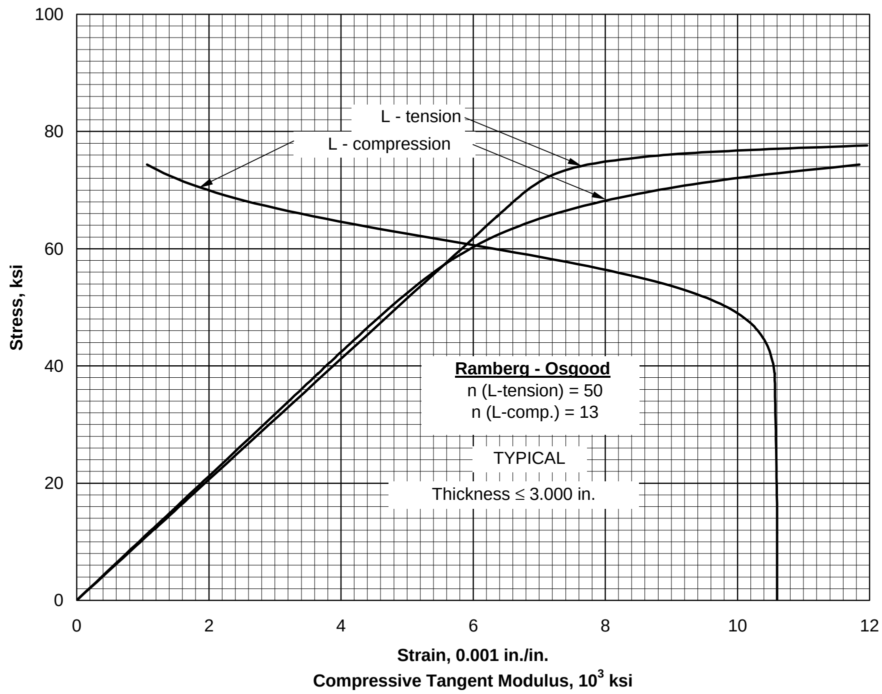

Figure 3.7.6.1.6(j). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T6 and T651 aluminum alloy rolled-bar, rod, and shape at room temperature.

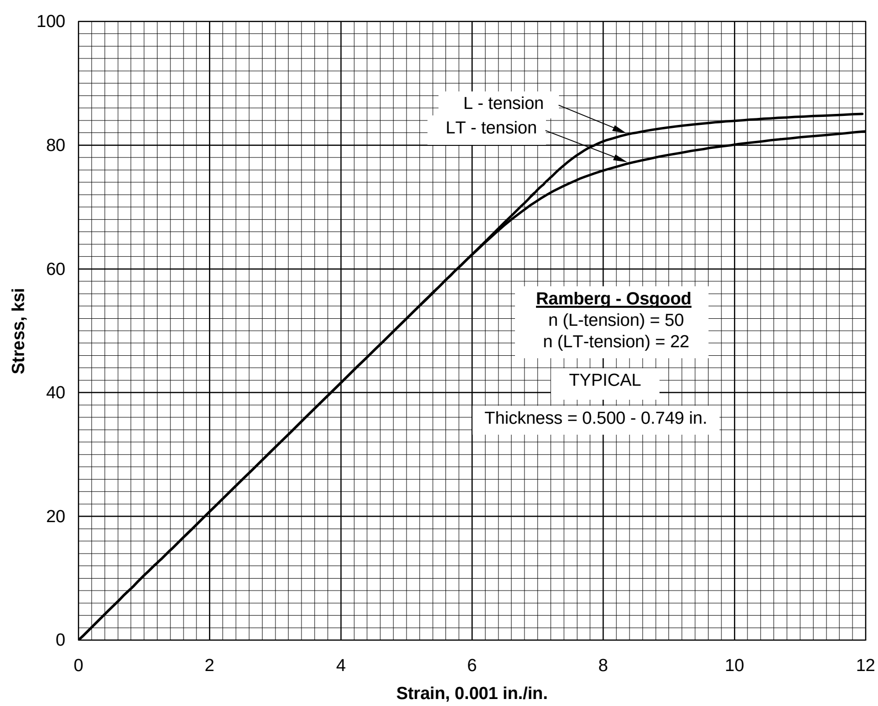

Figure 3.7.6.1.6(k). Typical tensile stress-strain curves for 7075-T651X aluminum alloy extrusion at room temperature.

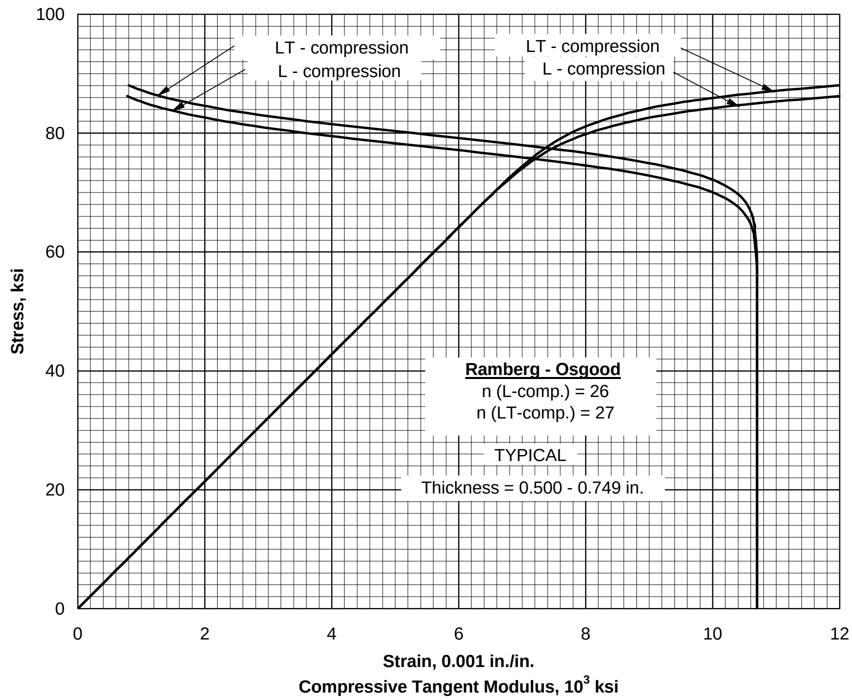

Figure 3.7.6.1.6(l). Typical compressive stress-strain and compressive tangent-modulus curve for 7075-T651X aluminum alloy extrusion at room temperature.

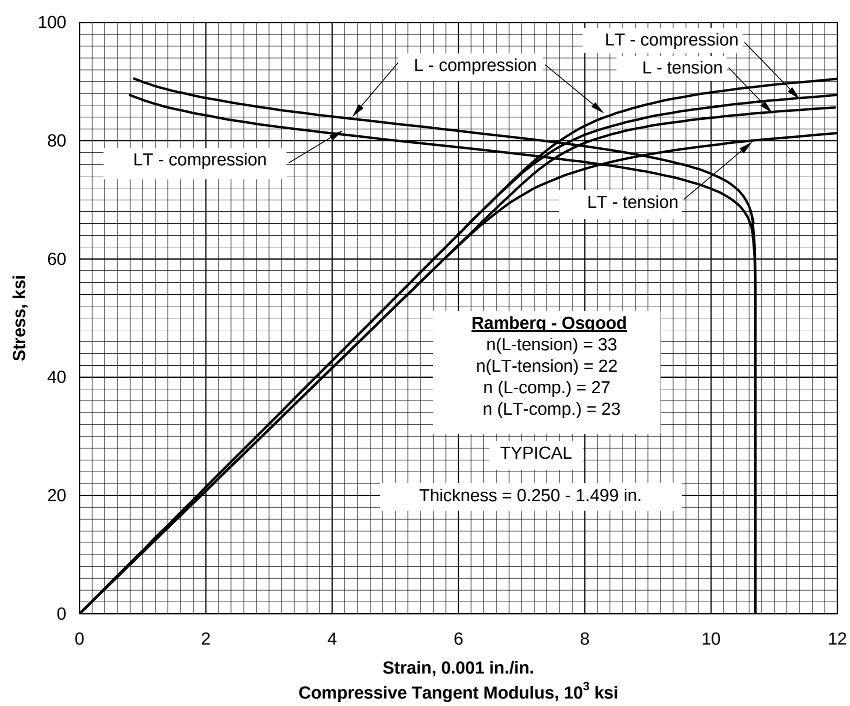

Figure 3.7.6.1.6(m). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T62 aluminum alloy extrusion at room temperature.

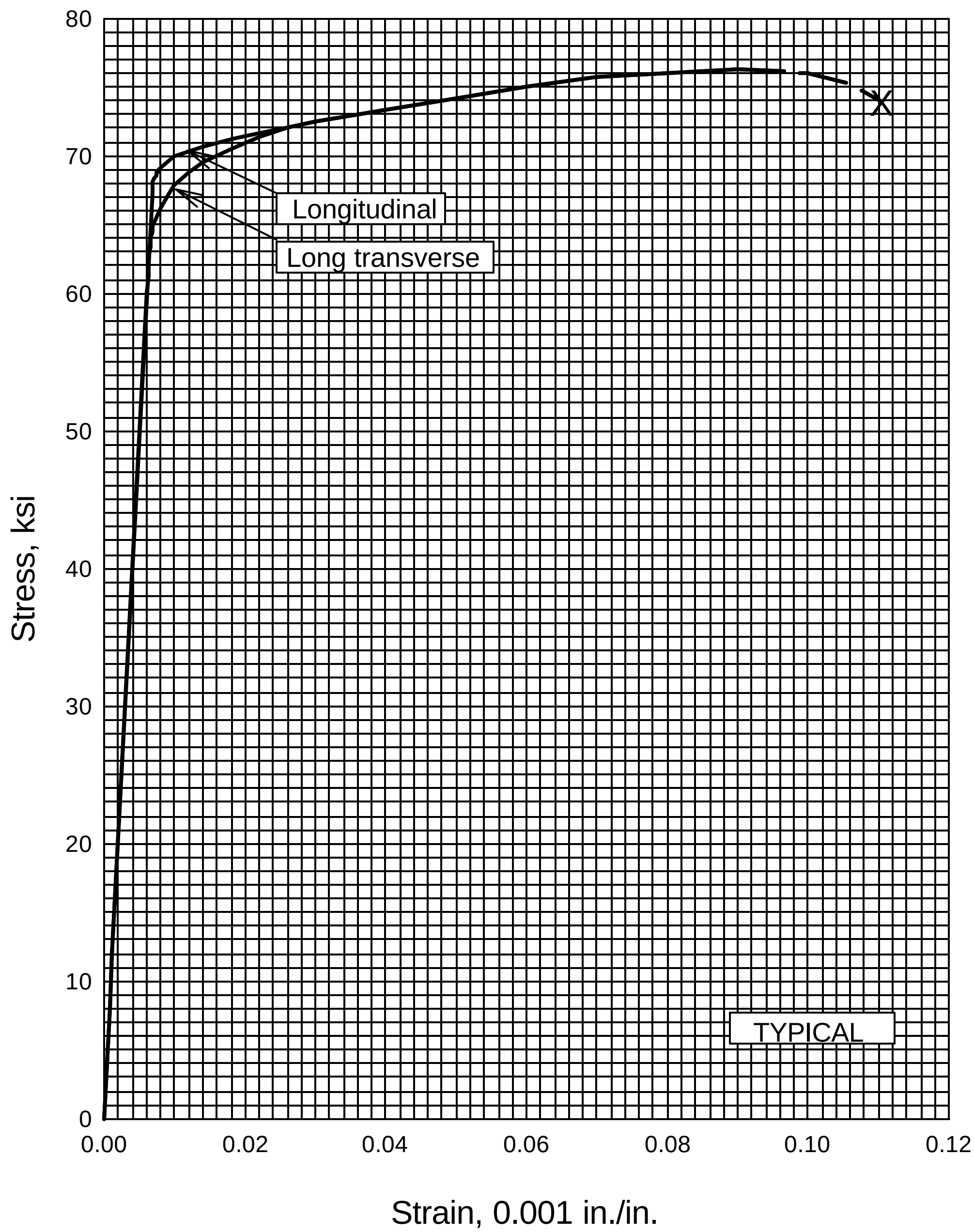

Figure 3.7.6.1.6(n). Typical tensile stress-strain curve (full range) for clad 7075-T6 aluminum alloy sheet at room temperature.

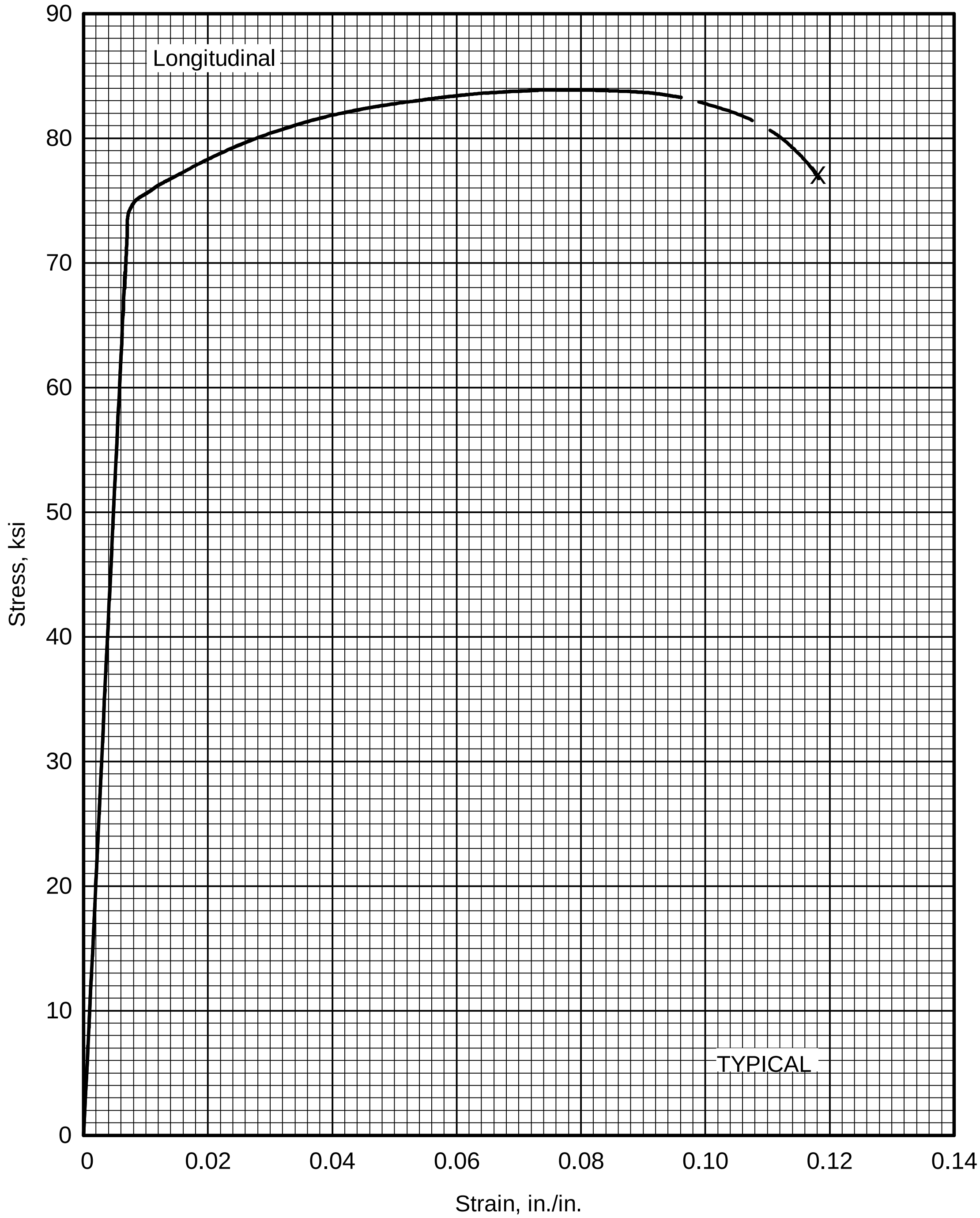

Figure 3.7.6.1.6(o). Typical tensile stress-strain curve (full range) for 7075-T6 and T651 aluminum alloy rolled or cold-finished bar at room temperature.

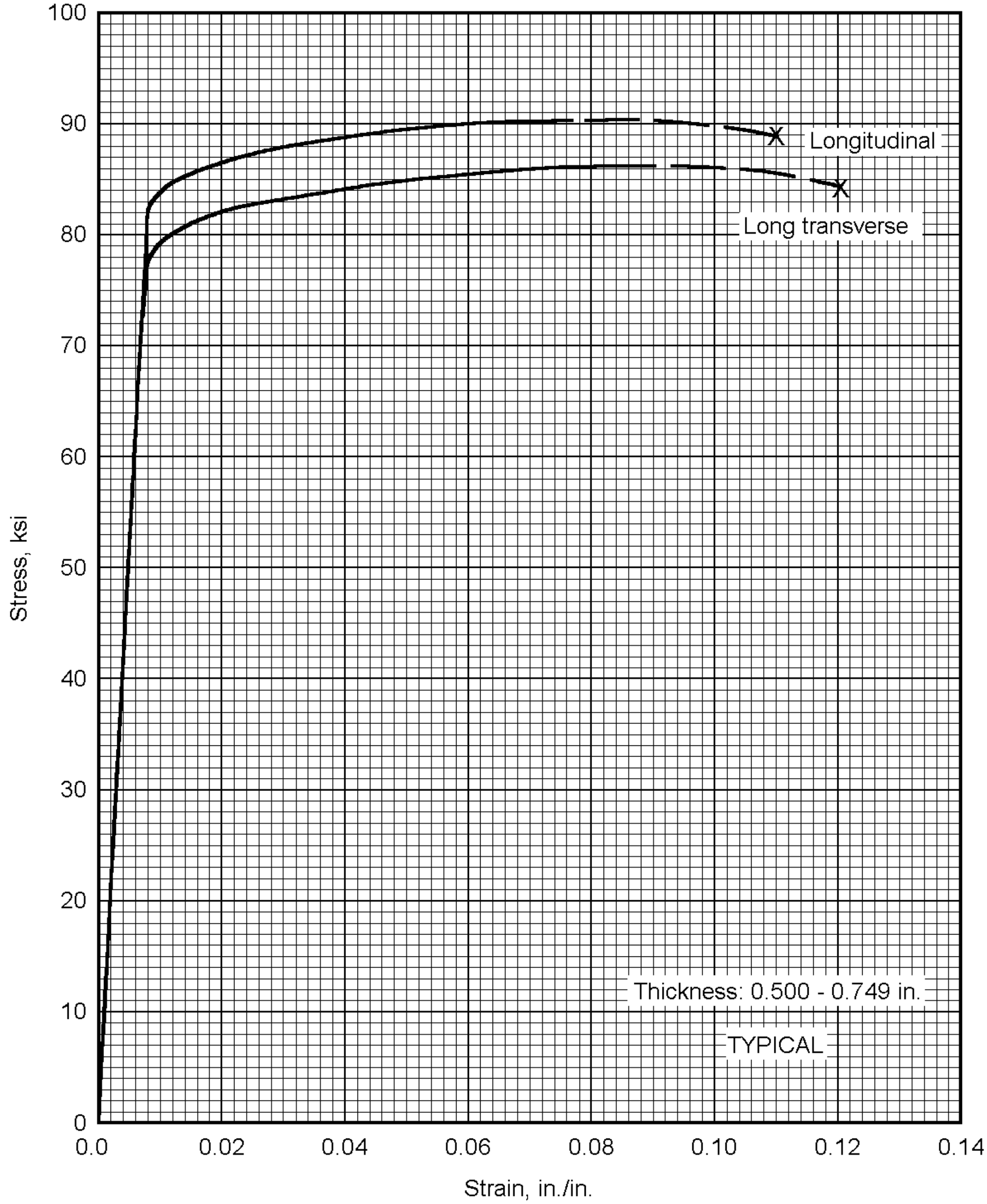

Figure 3.7.6.1.6(p). Typical tensile stress-strain curves (full range) for 7075-T651X aluminum alloy extrusion at room temperature.

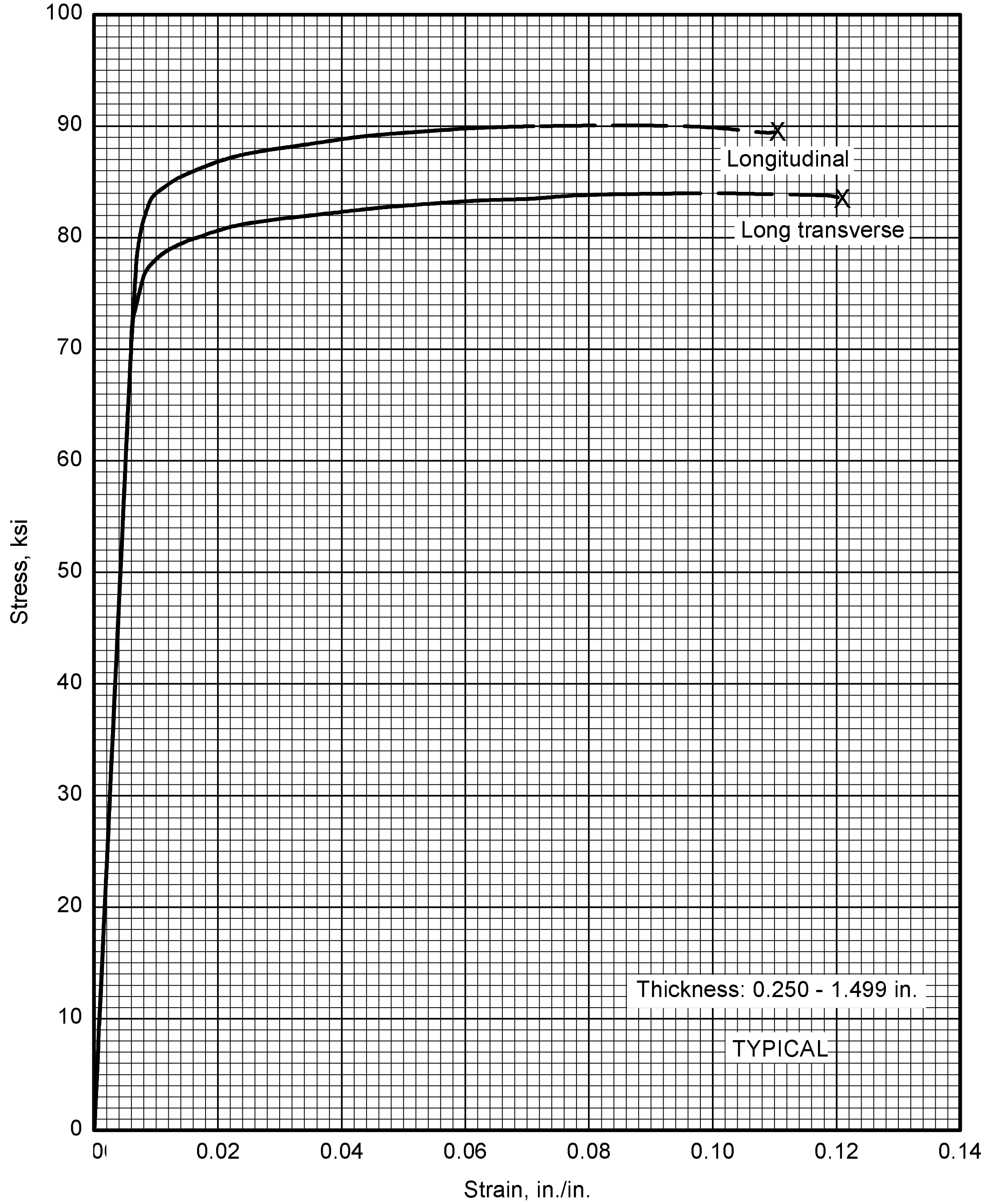

Figure 3.7.6.1.6(q). Typical tensile stress-strain curves (full range) for 7075-T62 aluminum alloy extrusion at room temperature.

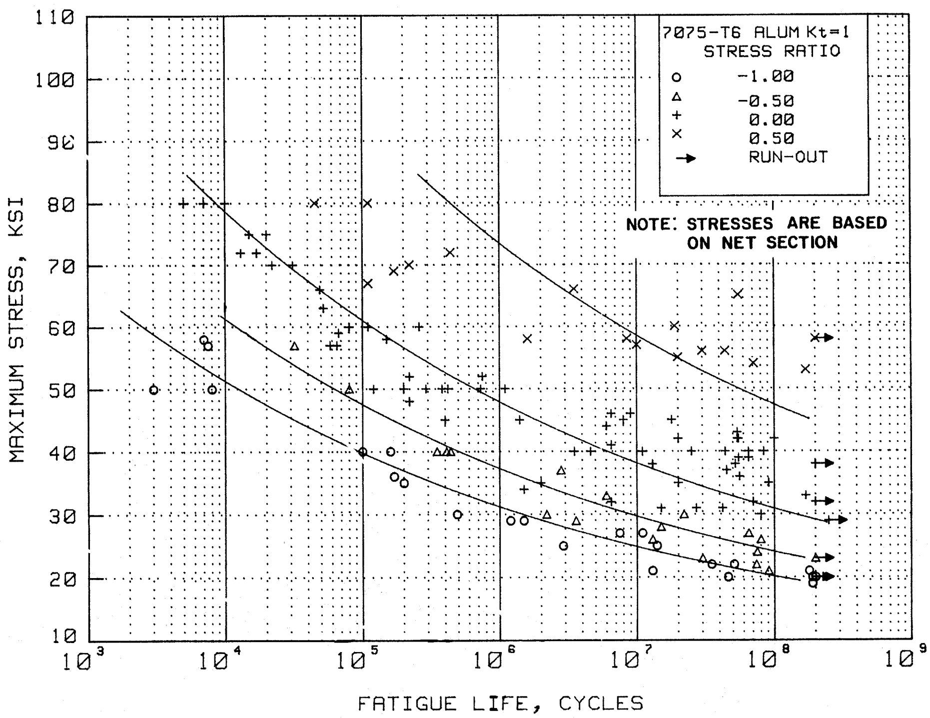

Figure 3.7.6.1.8(a). Best-fit S/N curves for unnotched 7075-T6 aluminum alloy, various product forms, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(a)

Product Form: 3/4-inch diam. drawn rod, 1-1/4-inch diam. rolled rod, and 1 x 7-1/2-inch bar, extruded 1-1/4-inch bar and 1-1/4-inch rod

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	82	72	RT

Specimen Details: Unnotched
Minimum diameter 0.200-inch

Surface Condition: Unspecified

Reference: 3.7.6.1.8

Test Parameters:
Loading - Axial
Frequency - 30 Hz
Temperature - RT
Environment - Air

No. of Heats/Lots: 8

Equivalent Stress Equation:
$\text{Log } N_f = 18.22\text{-}7.77 \log (S_{eq}\text{-}10.15)$
$S_{eq} = S_{max} (1\text{-}R)^{0.62}$
Std. Error of Estimate, Log (Life) = 0.626
Standard Deviation, Log (Life) = 1.435
R^2 = 81%

Sample Size = 130

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

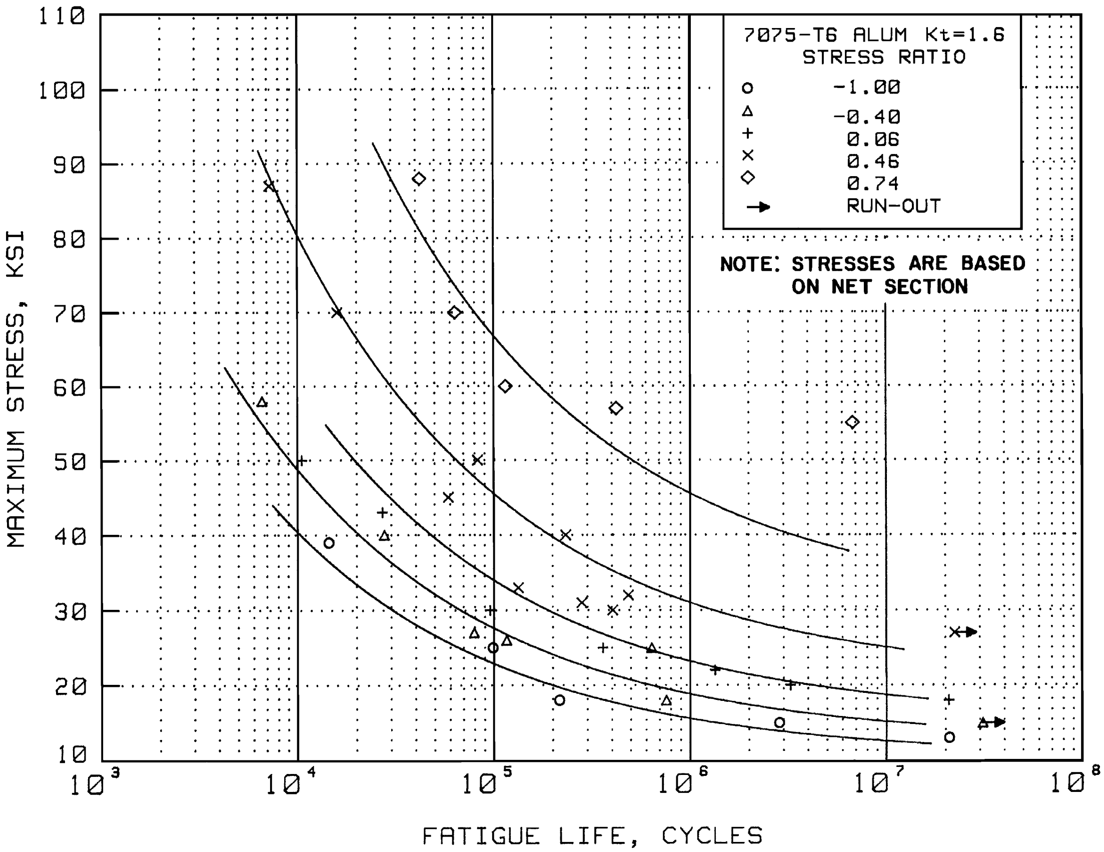

Figure 3.7.6.1.8(b). Best-fit S/N curve for notched, K_t = 1.6, 7075-T6 aluminum alloy rolled bar, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(b)

Product Form: 1-1/8-inch diam. rolled bar

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	99.2	—	RT

Specimen Details: Notched, K_t = 1.6
Notch-root-radius = 0.100
Test section diameter (Net) = 0.400 inches
Gross diameter = 0.450 inch
60° groove

Surface Condition: Polished to 10 micro-inches

Reference: 3.2.1.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 60 Hz
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
Log N_f = 8.26-2.62 log (S_{eq}-15.3)
$S_{eq} = S_{max}\ (1-R)^{0.525}$
Std. Error of Estimate, Log (Life) = 0.418
Standard Deviation, Log (Life) = 0.985
R^2 = 82%

Sample Size = 34

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

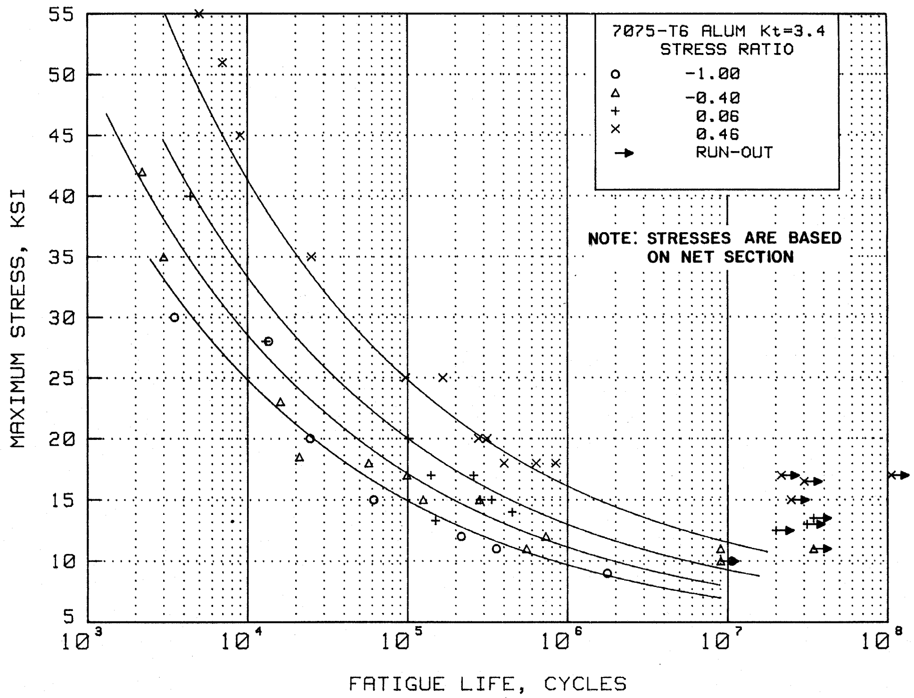

Figure 3.7.6.1.8(c). Best-fit S/N curves for notched, K_t = 3.4, 7075-T6 aluminum alloy rolled bar, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(c)

Product Form: 1-1/8-inch diam. rolled bar

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	96.5	—	RT

Specimen Details: Notched, K_t = 3.4
Notch-root-radius = 0.010
Test section diameter (Net) = 0.400 inch
Gross diameter = 0.450 inch
60° groove

Surface Condition: Polished to 10 micro-inches

Reference: 3.2.1.1.8(b)

Test Parameters:
Loading - Axial
Frequency - 60 Hz
Temperature - RT
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:
Log N_f = 9.19-3.646 log (S_{eq}-5.36)
$S_{eq} = S_{max}\ (1\text{-}R)^{0.386}$
Std. Error of Estimate, Log (Life) = 0.282
Standard Deviation, Log (Life) = 0.782
R^2 = 87%

Sample Size = 48

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

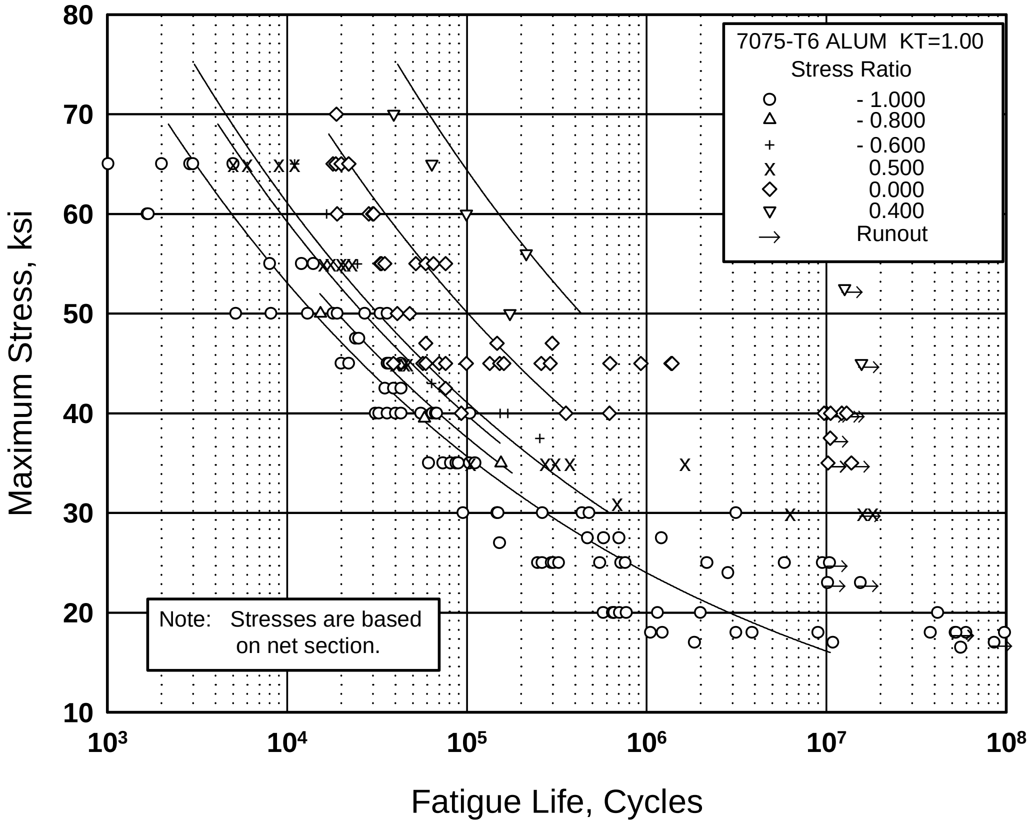

Figure 3.7.6.1.8(d). Best-fit S/N curves for unnotched 7075-T6 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(d)

Product Form: Bare sheet, 0.090-inch

Properties: TUS, ksi — TYS, ksi — Temp., °F

TUS, ksi	TYS, ksi	Temp., °F
82	76	RT

Specimen Details: Unnotched
0.5 to 1.0-inch width

Surface Condition: Electropolished
150 grit emery paper

References: 3.2.3.1.8(a) and (f)

Test Parameters:
Loading - Axial
Frequency - 300 to 1800 cpm
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 14.86-5.80 log (S_{eq})
$S_{eq} = S_{max}$ (1-R)$^{0.49}$
Std. Error of Estimate, Log (Life) = 0.41
Standard Deviation, Log (Life) = 0.92
R^2 = 80%

Sample Size = 176

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

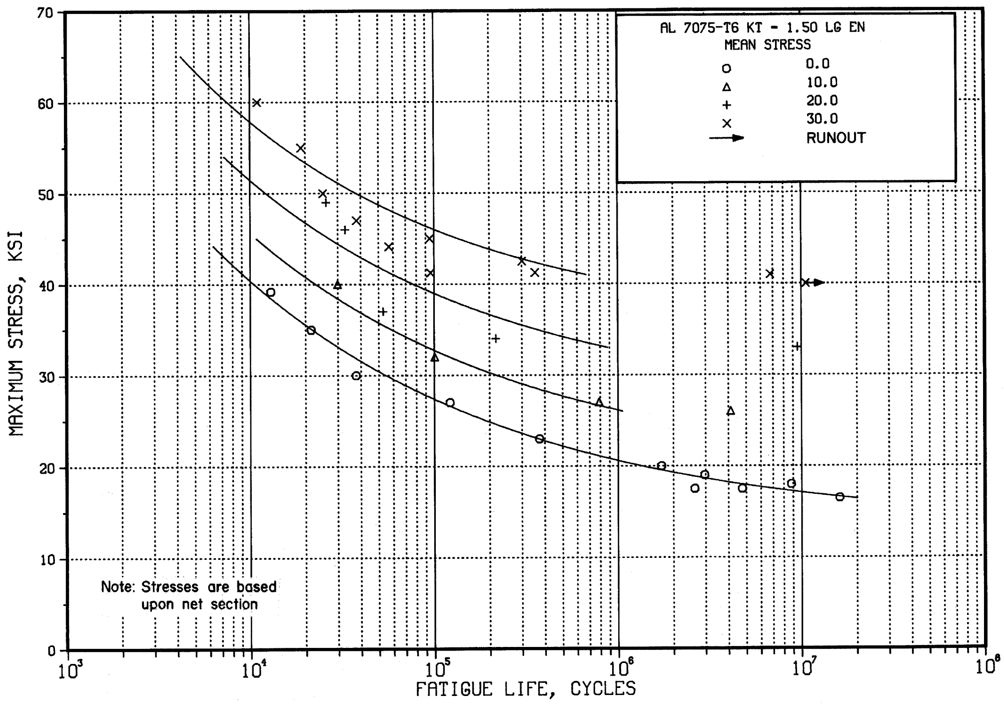

Figure 3.7.6.1.8(e). Best-fit S/N curves for notched, K_t = 1.5, 7075-T6 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(e)

Product Form: Bare sheet, 0.090-inch

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	82	76	RT (unnotched)
	87	—	RT (notched)

Specimen Details: Edge Notched
3.000-inches gross width
1.500-inches net width
0.760-inch notch radius
60° flank angle

Surface Condition: Electropolished

Reference: 3.2.3.1.8(d)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 9.54-3.52 log (S_{eq}-18.7)
$S_{eq} = S_{max}$ $(1-R)^{0.49}$
Std. Error of Estimate, Log (Life) = 0.41
Standard Deviation, Log (Life) = 1.00
R^2 = 83%

Sample Size = 30

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

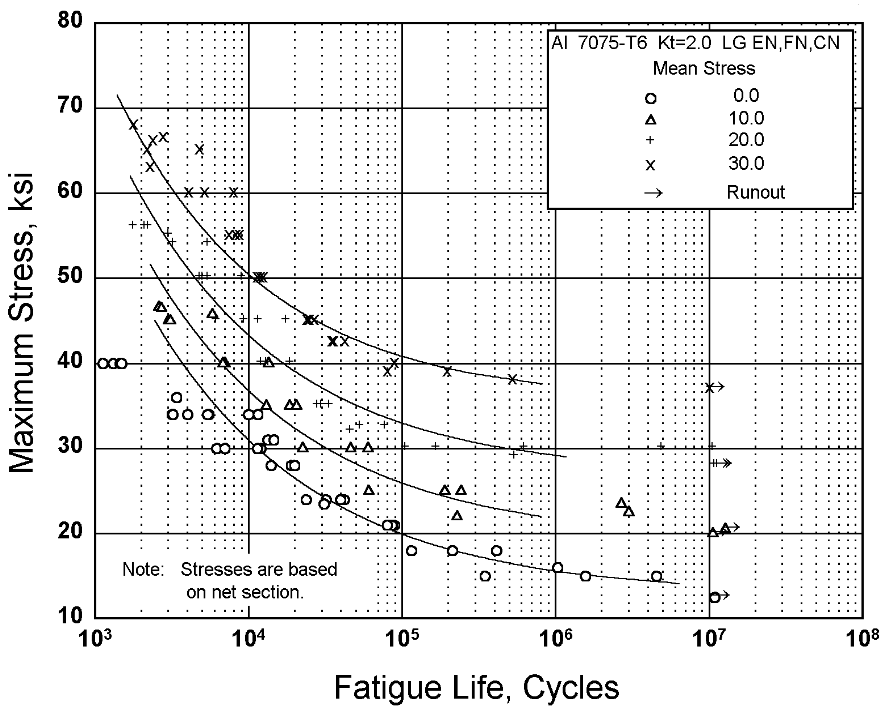

Figure 3.7.6.1.8(f). Best-fit S/N curves for notched, K_t = 2.0, 7075-T6 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(f)

Product Form: Bare sheet, 0.090-inch

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	82	76	RT (unnotched)
	88	—	RT (notched)

Specimen Details: Notched

Notch Type	Gross Width	Net Width	Notch Radius
Center	4.50	1.50	1.50
Edge	2.25	1.50	0.3175
Fillet	2.25	1.50	0.1736

Surface Condition: Electropolished

References: 3.2.3.1.8(b) and (f)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 7.50\text{-}2.46 \log (S_{eq}\text{-}18.6)$
$S_{eq} = S_{max} (1\text{-}R)^{0.54}$
Std. Error of Estimate, Log (Life) = 0.31
Standard Deviation, Log (Life) = 0.85
R^2 = 87%

Sample Size = 112

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

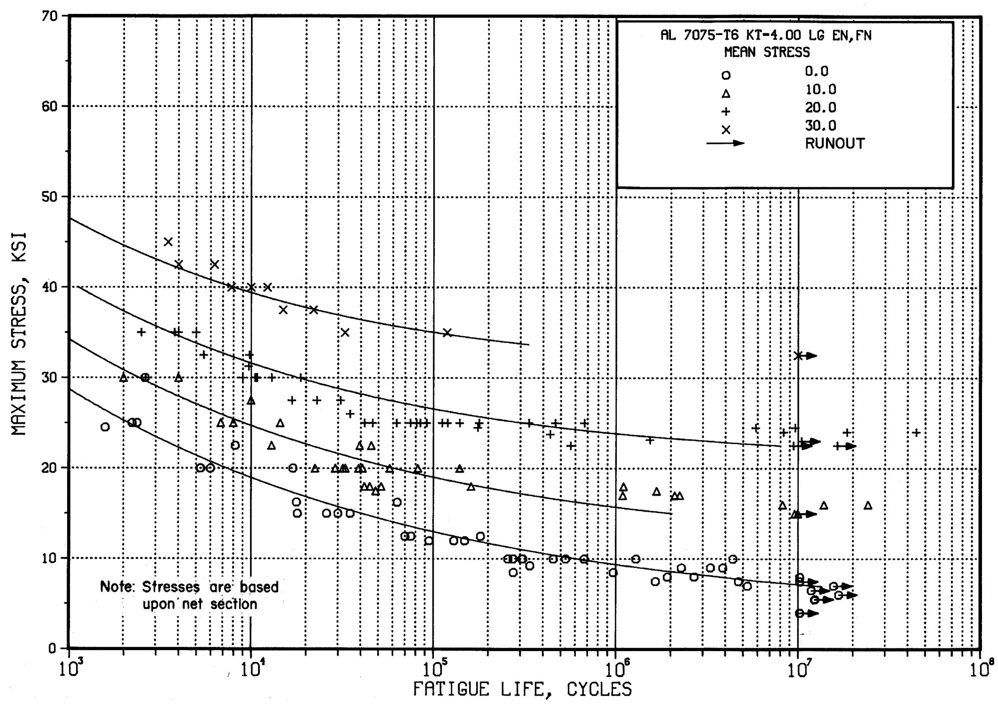

Figure 3.7.6.1.8(g). Best-fit S/N curves for notched, K_t = 4.0, 7075-T6 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(g)

Product Form: Bare sheet, 0.090-inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
82	76	RT (unnotched)
82	—	RT (notched)

Specimen Details: Notched

Notch Type	Gross Width	Net Width	Notch Radius
Edge	2.25	1.500	0.057
Edge	4.10	1.500	0.070
Fillet	2.25	1.500	0.0195

Surface Condition: Electropolished

References: 3.2.3.1.8(b), (f), (g), and (h)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1800 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 10.2-4.63 log (S_{eq}-5.3)
$S_{eq} = S_{max} (1-R)^{0.51}$
Std. Error of Estimate, Log (Life) = 0.51
Standard Deviation, Log (Life) = 1.08
R^2 = 78%

Sample Size = 126

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

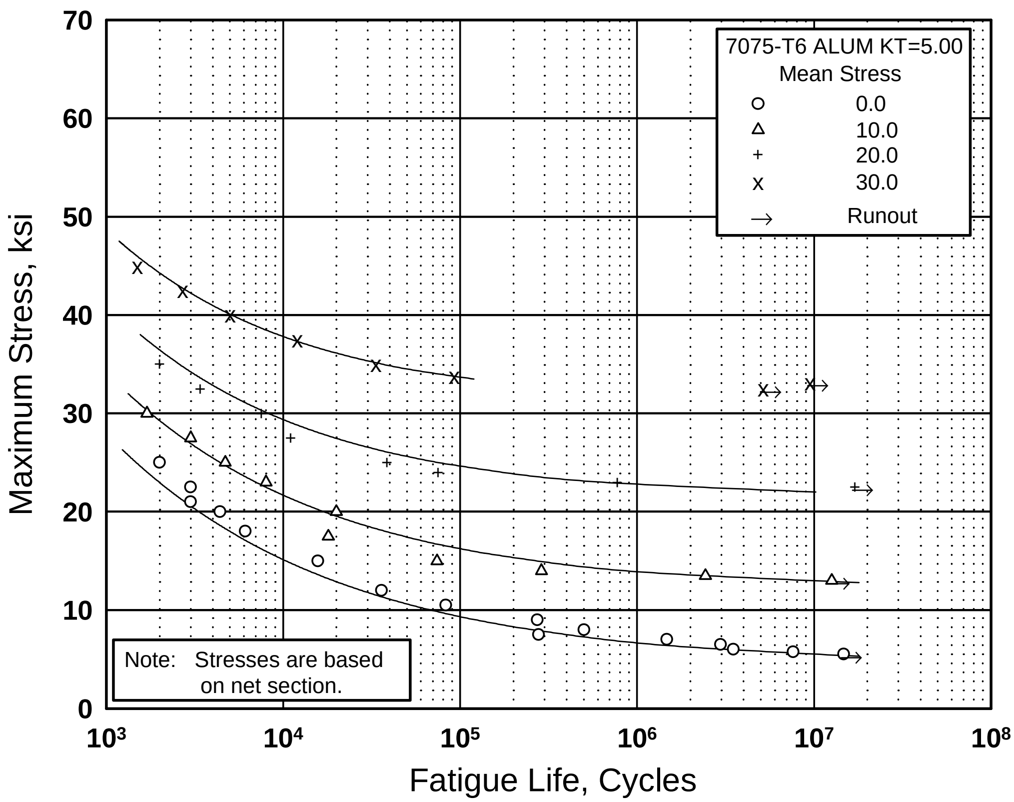

Figure 3.7.6.1.8(h). Best-fit S/N curves for notched, K_t = 5.0, 7075-T6 aluminum alloy sheet, longitudinal direction.

Correlative Information for Figure 3.7.6.1.8(h)

Product Form: Bare sheet, 0.090-inch

Properties:

	TUS, ksi	TYS, ksi	Temp., °F
	82	76	RT (unnotched)
	77	—	RT (notched)

Specimen Details: Edge Notched
2.25-inch gross width
1.500-inch net width
0.03125-inch notch radius

Surface Condition: Electropolished

Reference: 3.2.3.1.8(c)

Test Parameters:
Loading - Axial
Frequency - 1100 to 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
Log N_f = 7.51-2.92 log (S_{eq}-6.7)
$S_{eq} = S_{max} (1-R)^{0.58}$
Std. Error of Estimate, Log (Life) = 0.23
Standard Deviation, Log (Life) = 1.08
R^2 = 95%

Sample Size = 37

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

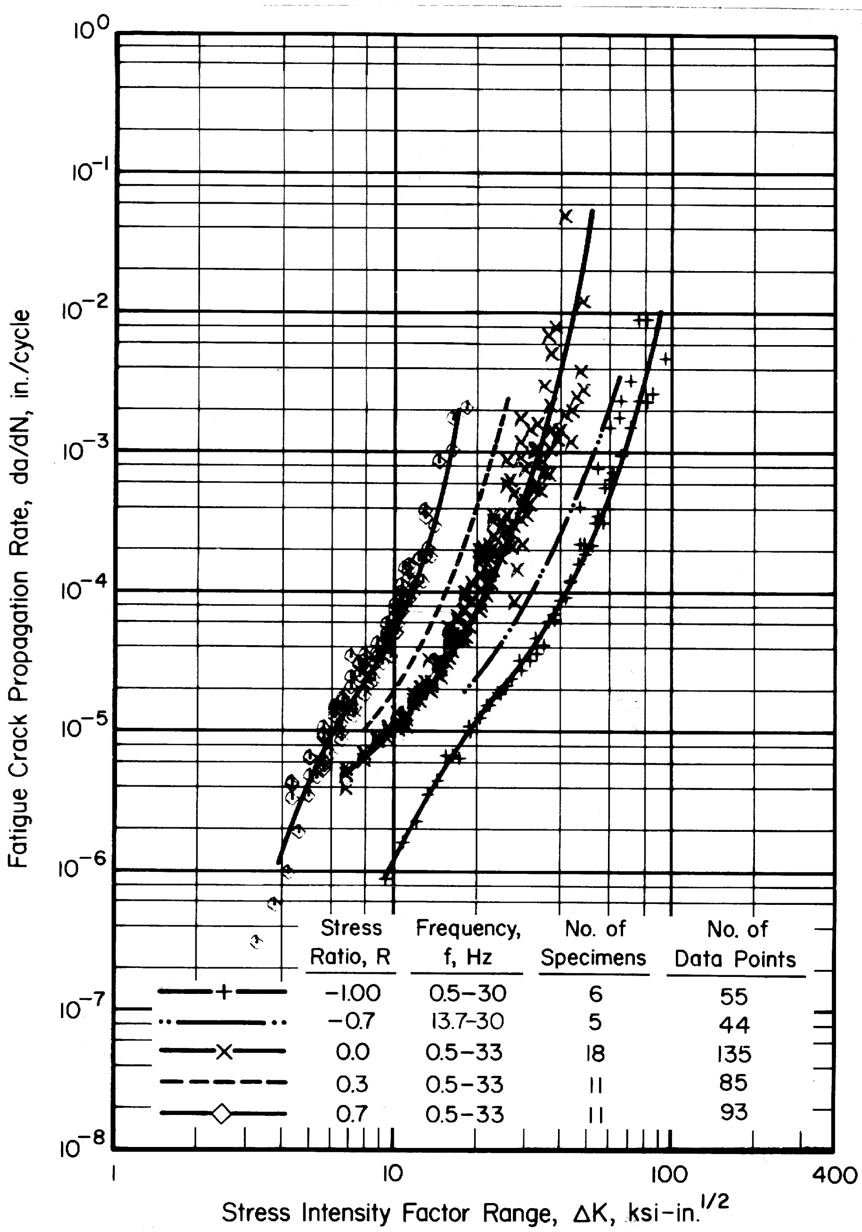

Figure 3.7.6.1.9. Fatigue-crack-propagation data for 0.090-inch-thick 7075-T6 aluminum alloy sheet with buckling restraint [References 3.7.6.1.9(a) through (e)].

Specimen Thickness:	*0.090 inch*	*Environment:*	*Lab air*
Specimen Width:	*1-1/2 - 12 inches*	*Temperature:*	*RT*
Specimen Type:	*M(T)*	*Orientation:*	*L-T*

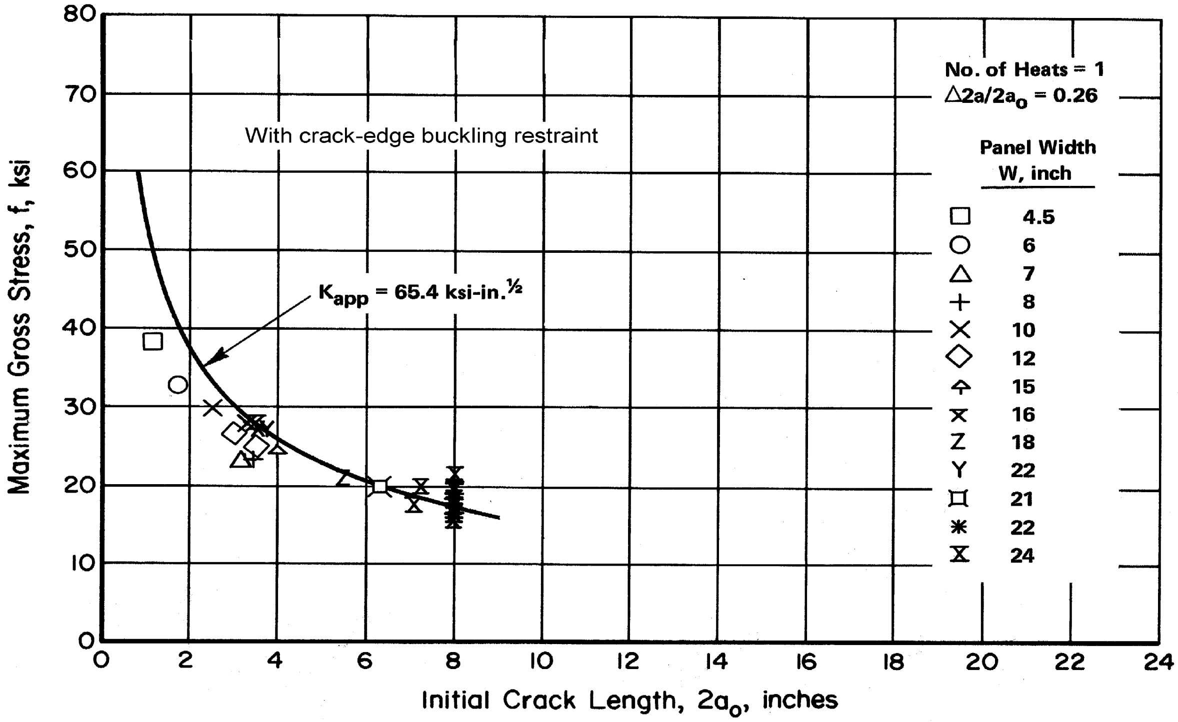

Figure 3.7.6.1.10(a). Residual strength behavior of 0.063-inch-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is T-L [Reference 3.1.2.1.6(f)].

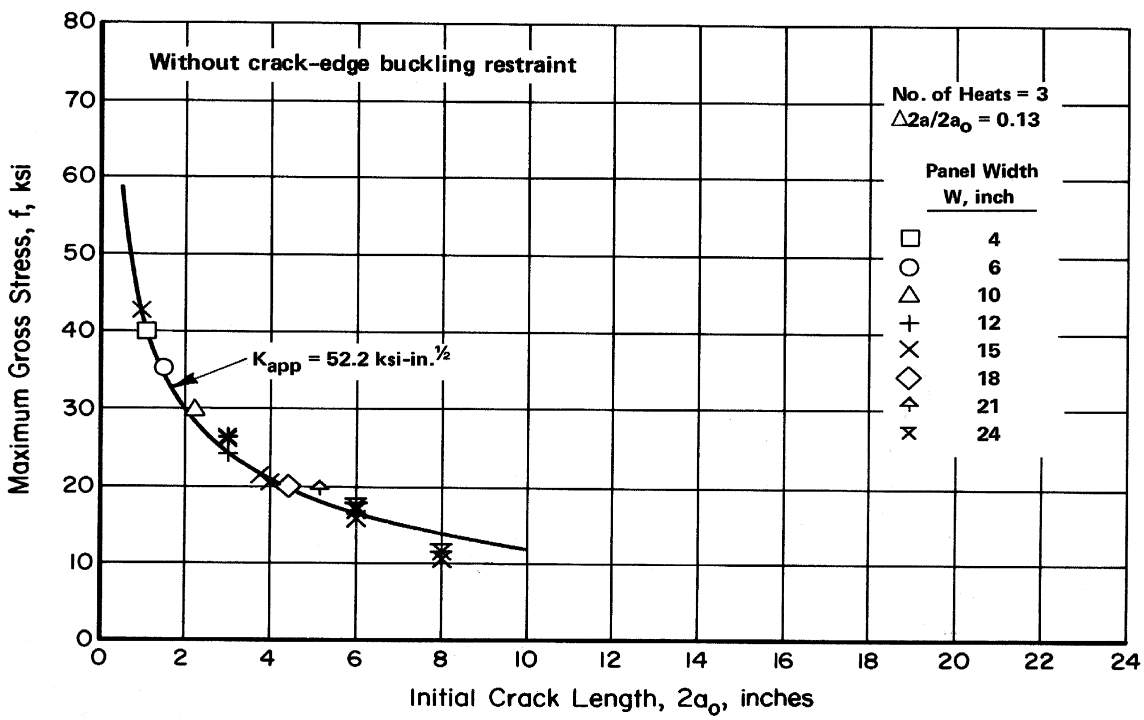

Figure 3.7.6.1.10(b). Residual strength behavior of 0.063-inch-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is T-L [References 3.1.2.1.6(d) and (f)].

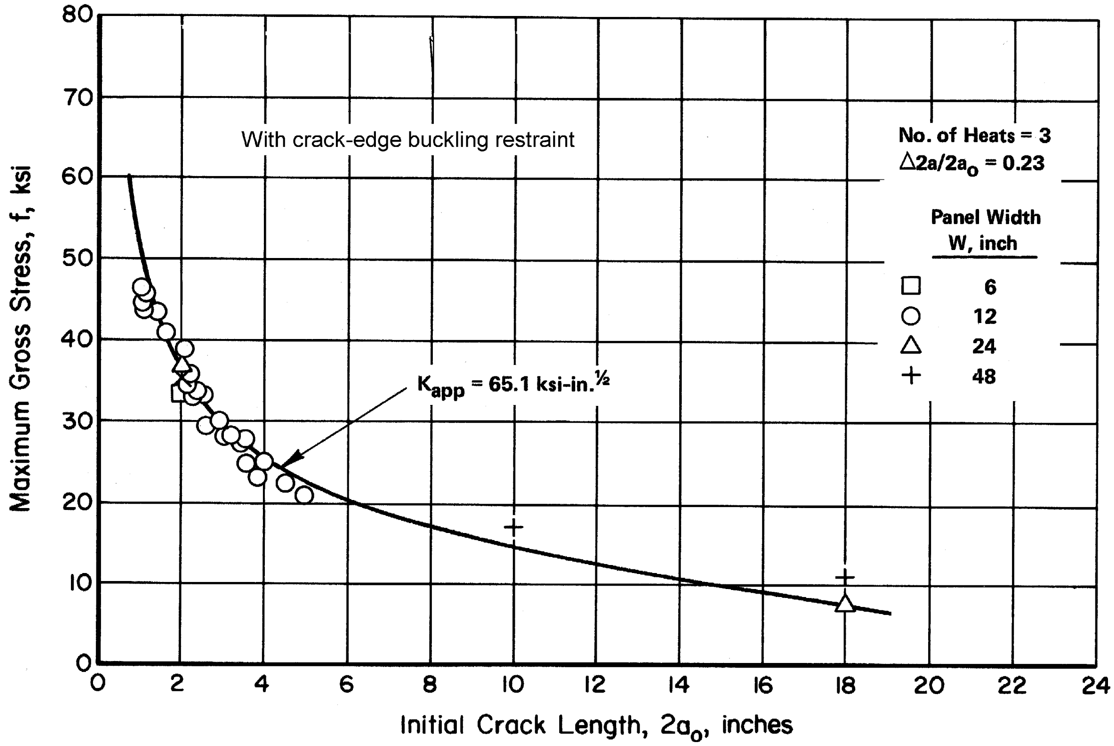

Figure 3.7.6.1.10(c). Residual strength behavior of 0.090- and 0.100-inch-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is L-T [References 3.1.2.1.6(e), (g), and 3.7.6.1.9(e)].

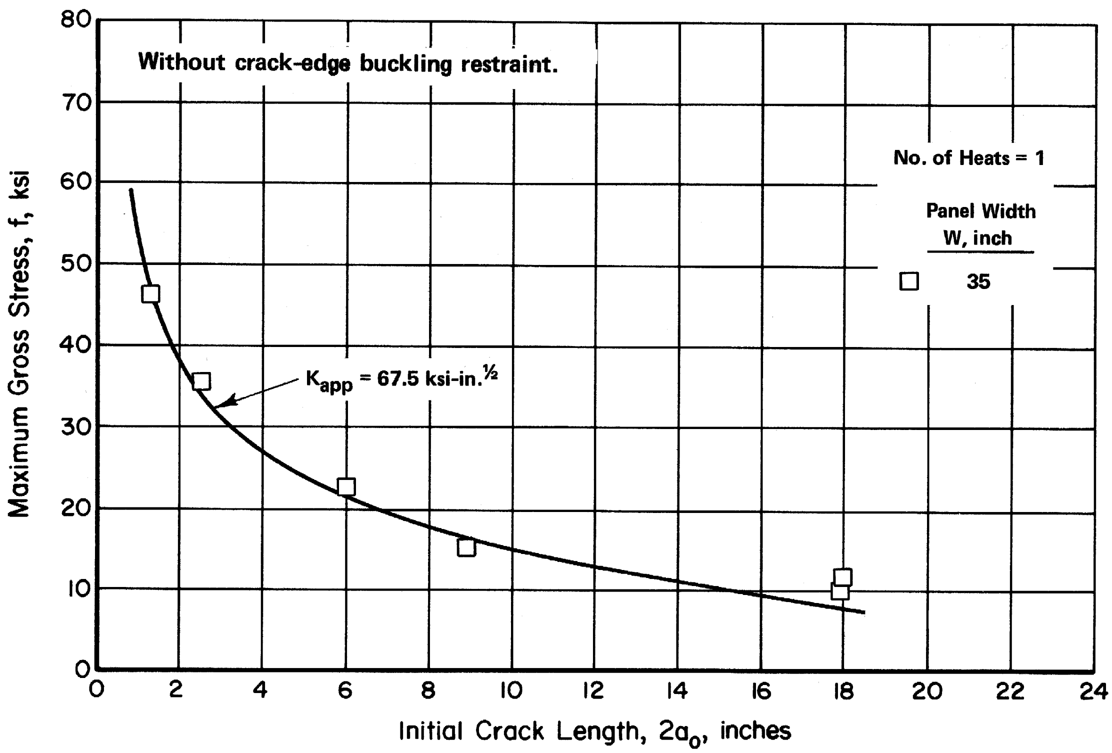

Figure 3.7.6.1.10(d). Residual strength behavior of 0.100-inch-thick 7075-T6 aluminum alloy sheet at room temperature. Crack orientation is L-T [Reference 3.1.2.1.6(g)].

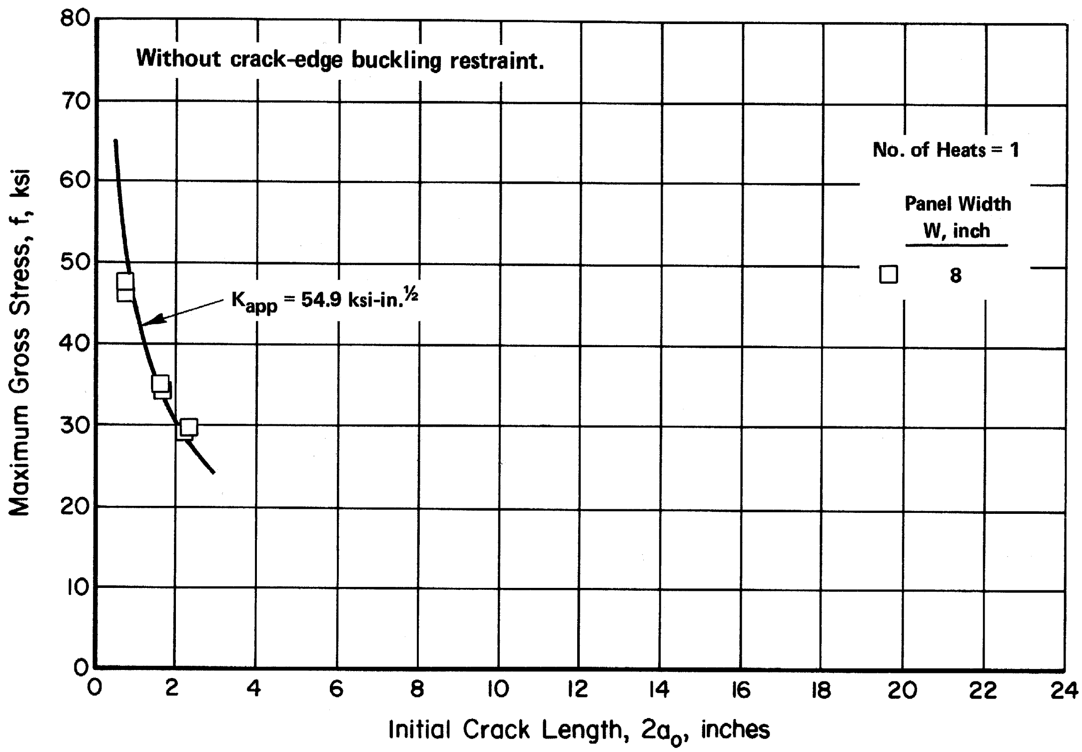

Figure 3.7.6.1.10(e). Residual strength behavior of 0.313-inch-thick 7075-T6 aluminum alloy plate at room temperature. Crack orientation is L-T [Reference 3.1.2.1.6(g)].

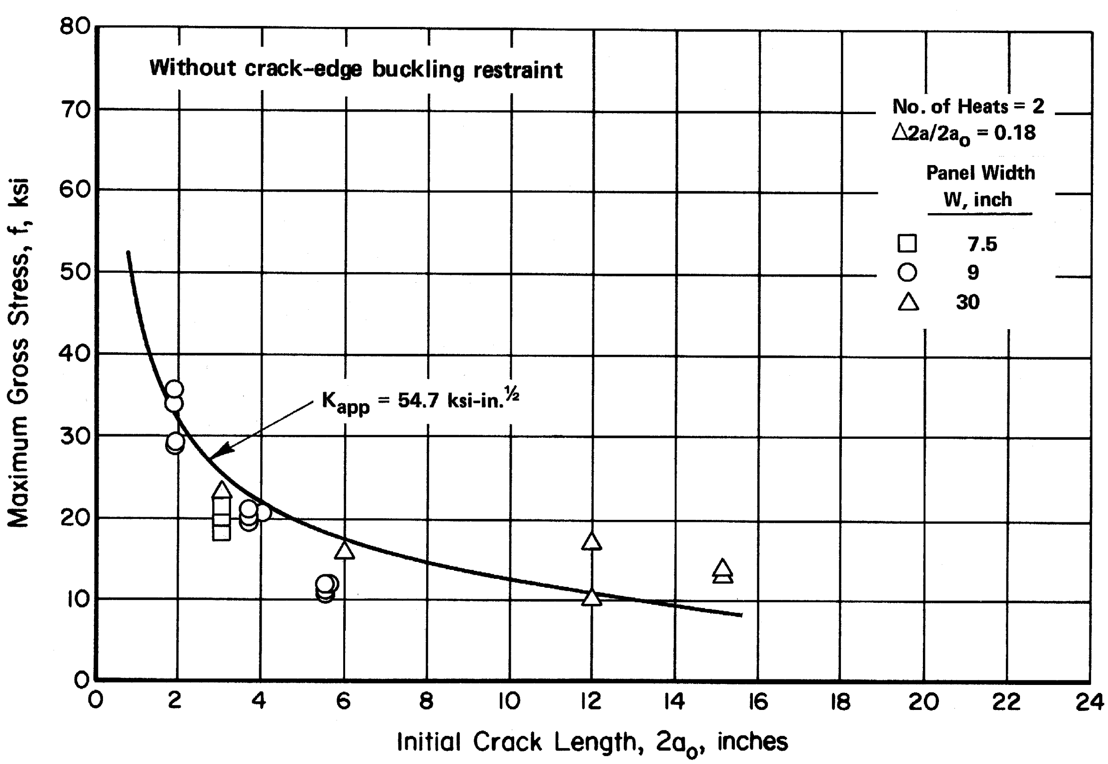

Figure 3.7.6.1.10(f). Residual strength behavior of 0.040-inch-thick 7075-T6 clad aluminum alloy sheet at room temperature. Crack orientation is L-T [References 3.1.2.1.6(f) and 3.7.6.1.10(f)].

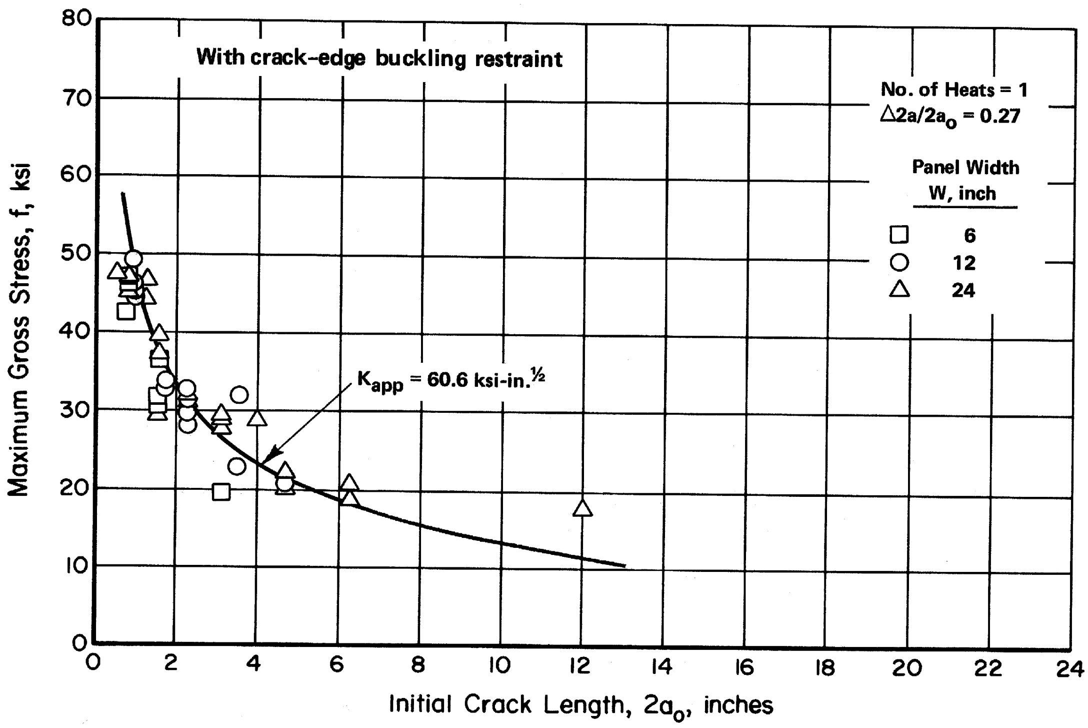

Figure 3.7.6.1.10(g). Residual strength behavior of 0.080-inch-thick 7075-T6 clad aluminum alloy sheet at room temperature. Crack orientation is L-T [References 3.1.2.1.6(h) and (i)].

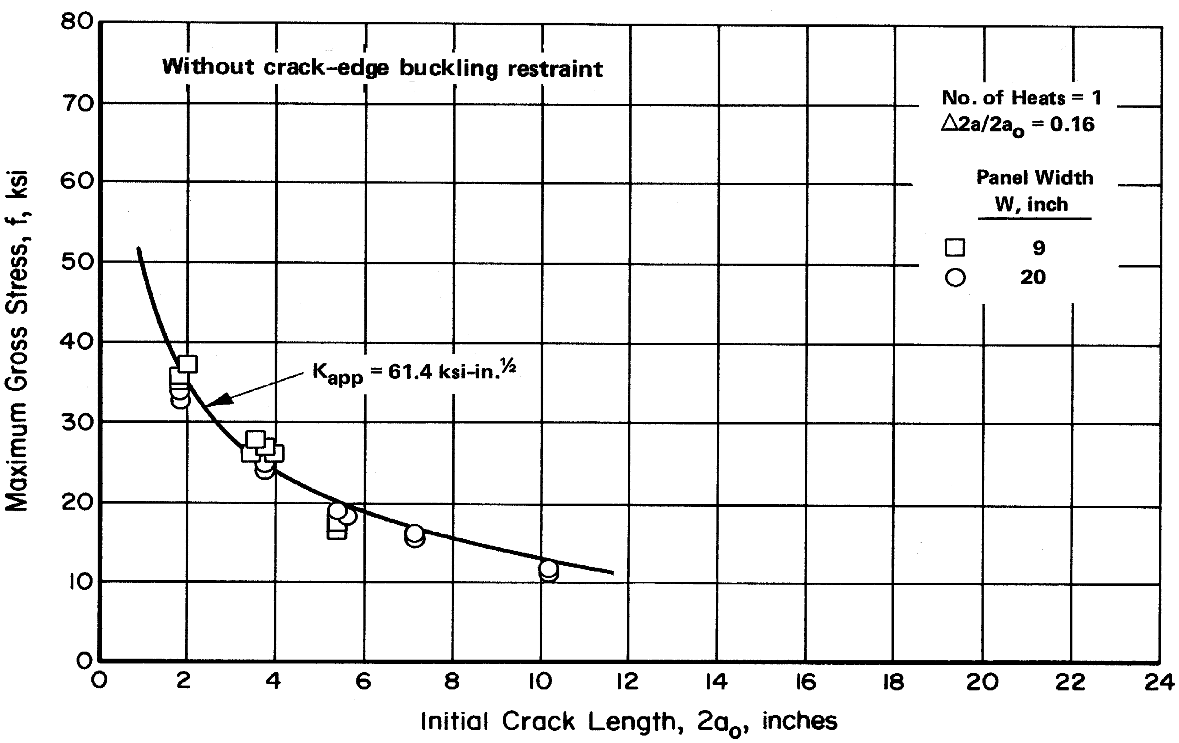

Figure 3.7.6.1.10(h). Residual strength behavior of 0.090-inch-thick 7075-T6 clad aluminum alloy sheet at room temperature. Crack orientation is L-T [Reference 3.7.6.1.10(f)].

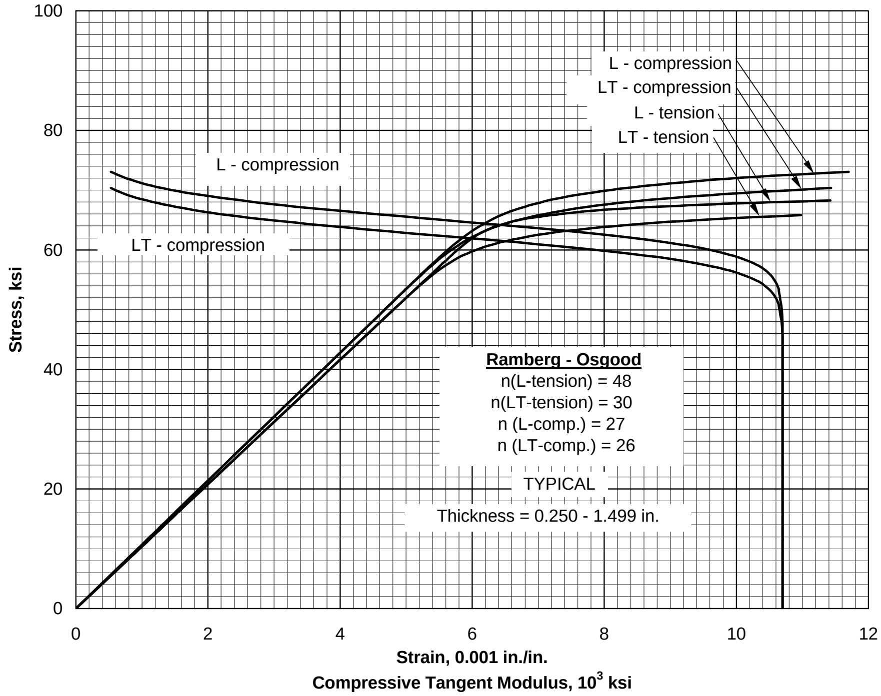

Figure 3.7.6.2.6(a). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T73 aluminum alloy extrusion at room temperature.

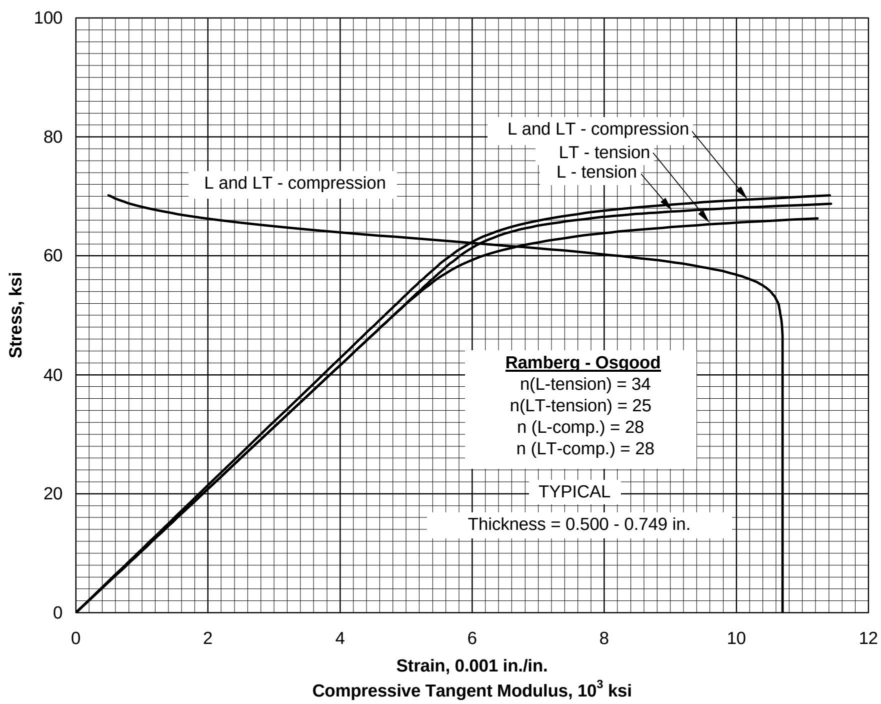

Figure 3.7.6.2.6(b). Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 7075-T7351X aluminum alloy extrusion at room temperature.

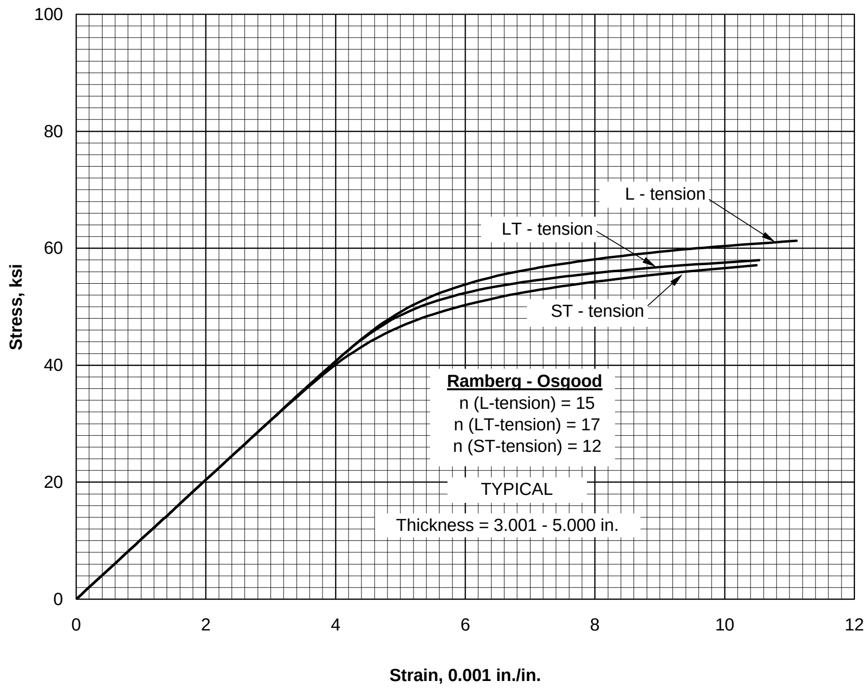

Figure 3.7.6.2.6(c). Typical tensile stress-strain curves for 7075-T7352 aluminum alloy hand forging at room temperature.

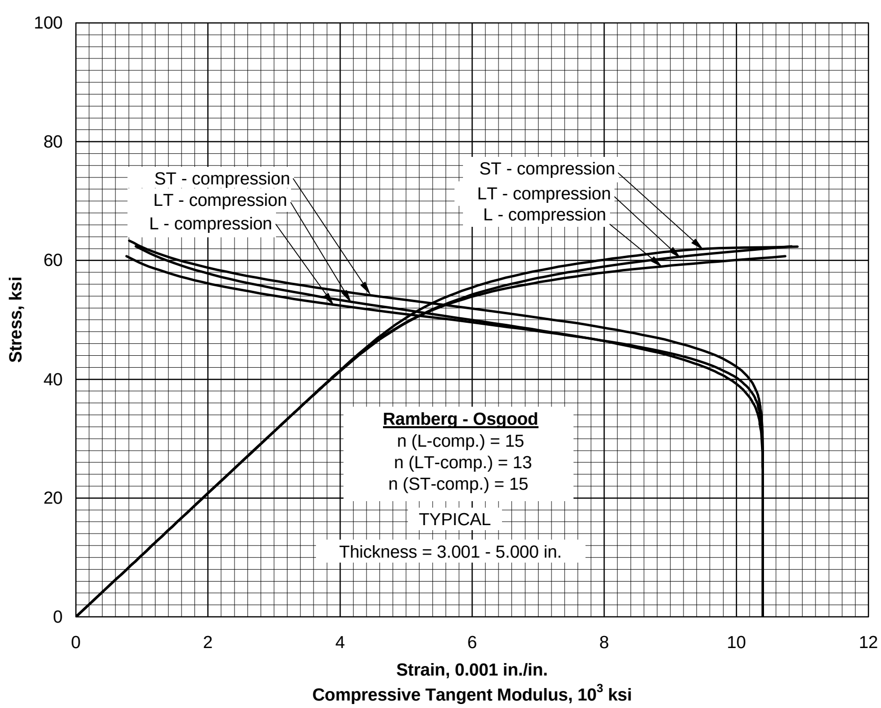

Figure 3.7.6.2.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7075-T7352 aluminum alloy hand forging at room temperature.

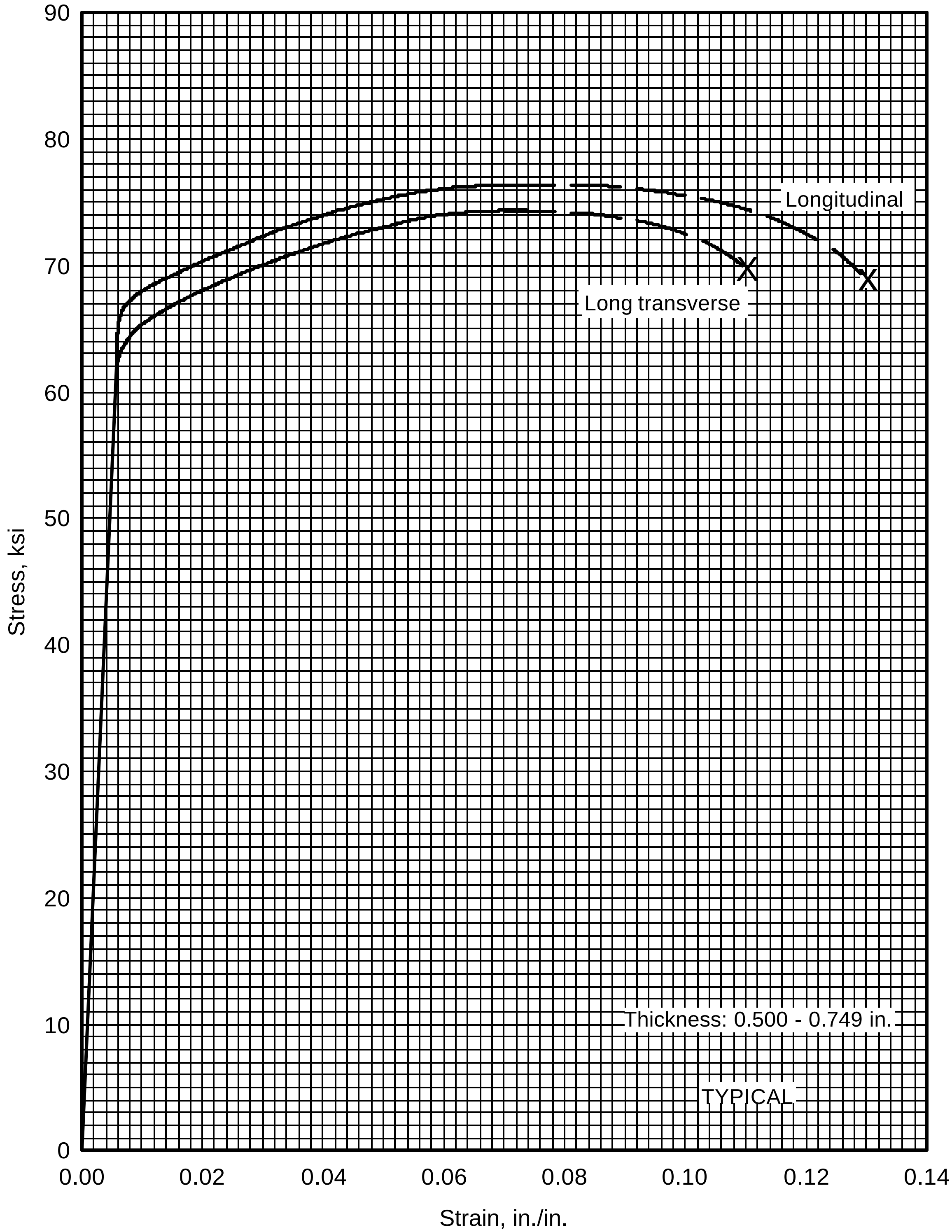

Figure 3.7.6.2.6(e). Typical tensile stress-strain curves (full range) for 7075-T7351X aluminum alloy extrusion at room temperature.

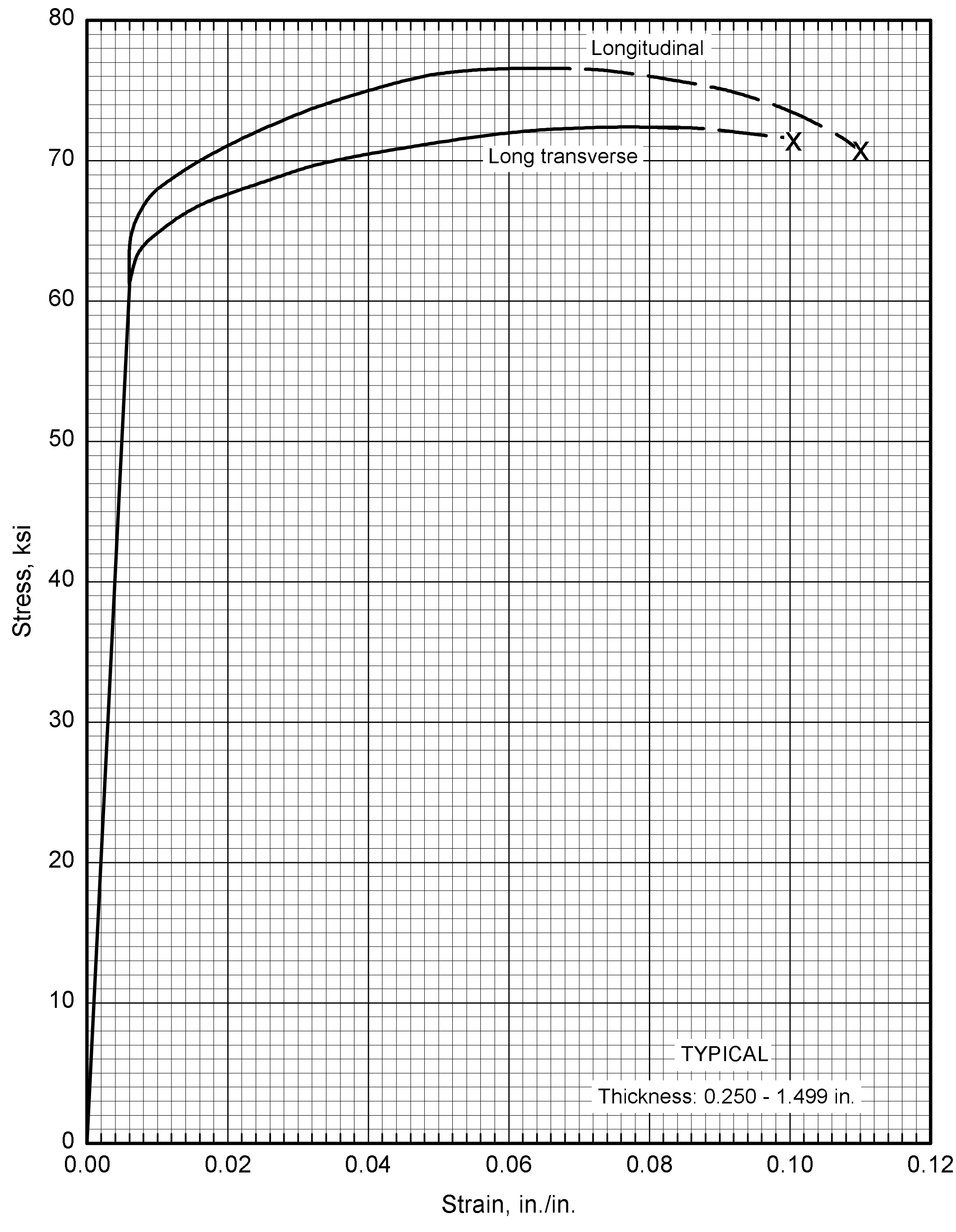

Figure 3.7.6.2.6(f). Typical tensile stress-strain curves (full range) for 7075-T73 aluminum alloy extrusion at room temperature.

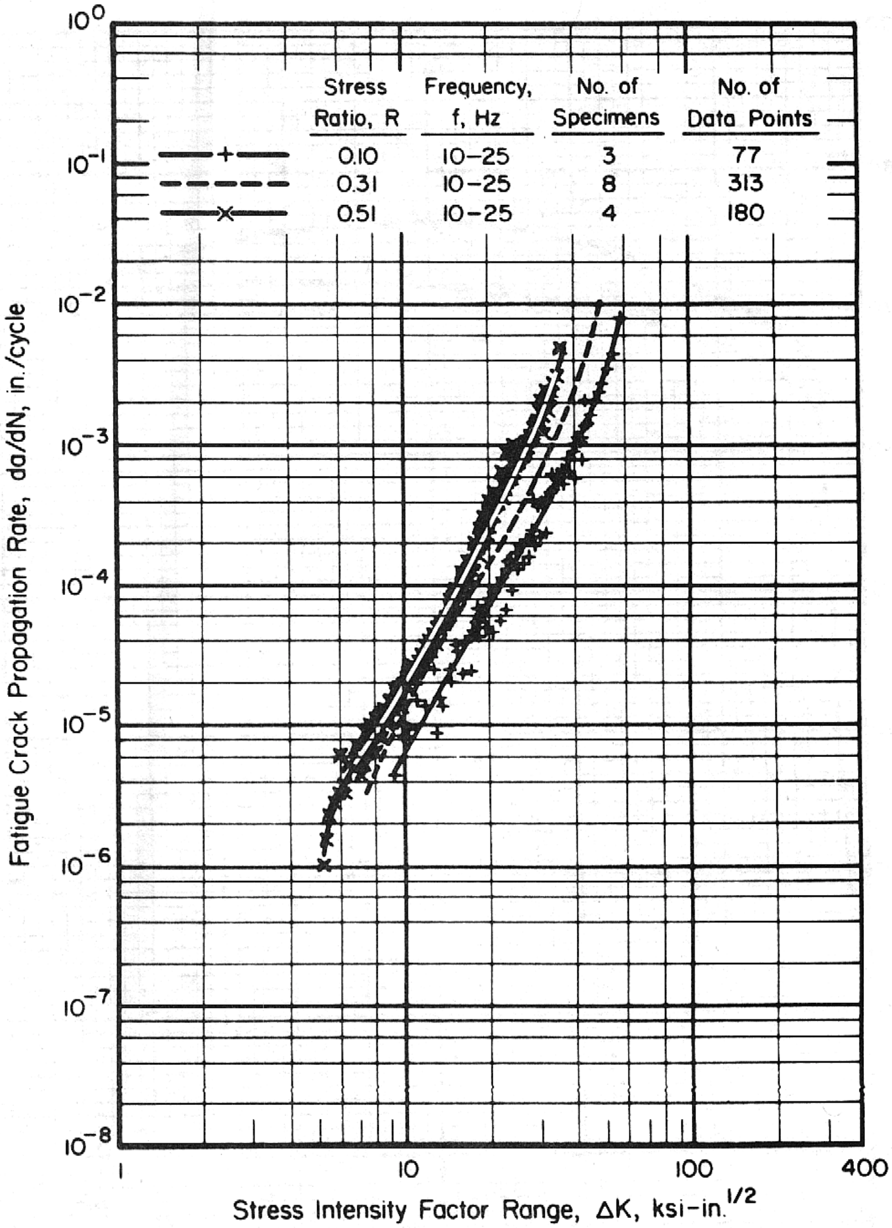

Figure 3.7.6.2.9(a). Fatigue-crack-propagation data for 0.250-inch-thick, 7075-T7351 aluminum alloy plate with buckling restraint [References 3.2.5.1.9(d) and 3.7.6.2.9(a)].

Specimen Thickness:	*0.250-inch*	*Environment:*	*50% R.H.*
Specimen Width:	*8, 16, 36-inches*	*Temperature:*	*RT*
Specimen Type:	*M(T)*	*Orientation:*	*L-T*

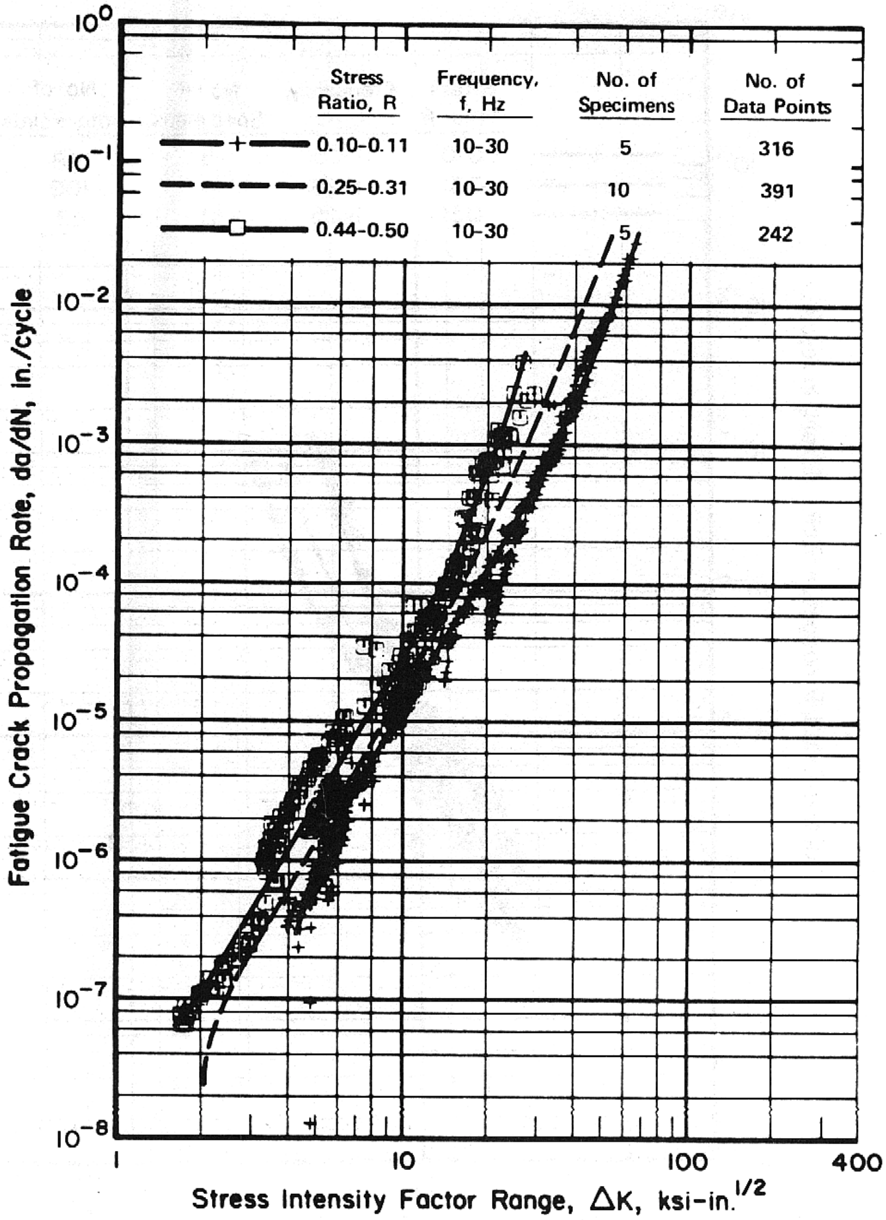

Figure 3.7.6.2.9(b). Fatigue-crack-propagation data for 0.500-inch-thick, 7075-T7351 aluminum alloy plate with buckling restraint [References 3.1.2.1.6(j) and 3.7.6.2.9(a) through (c)].

Specimen Thickness:	*0.475 to 0.500-inch*	*Environment:*	*50-95% R.H.*
Specimen Width:	*6, 8, 16, 36-inches*	*Temperature:*	*RT*
Specimen Type:	*M(T)*	*Orientation:*	*L-T*

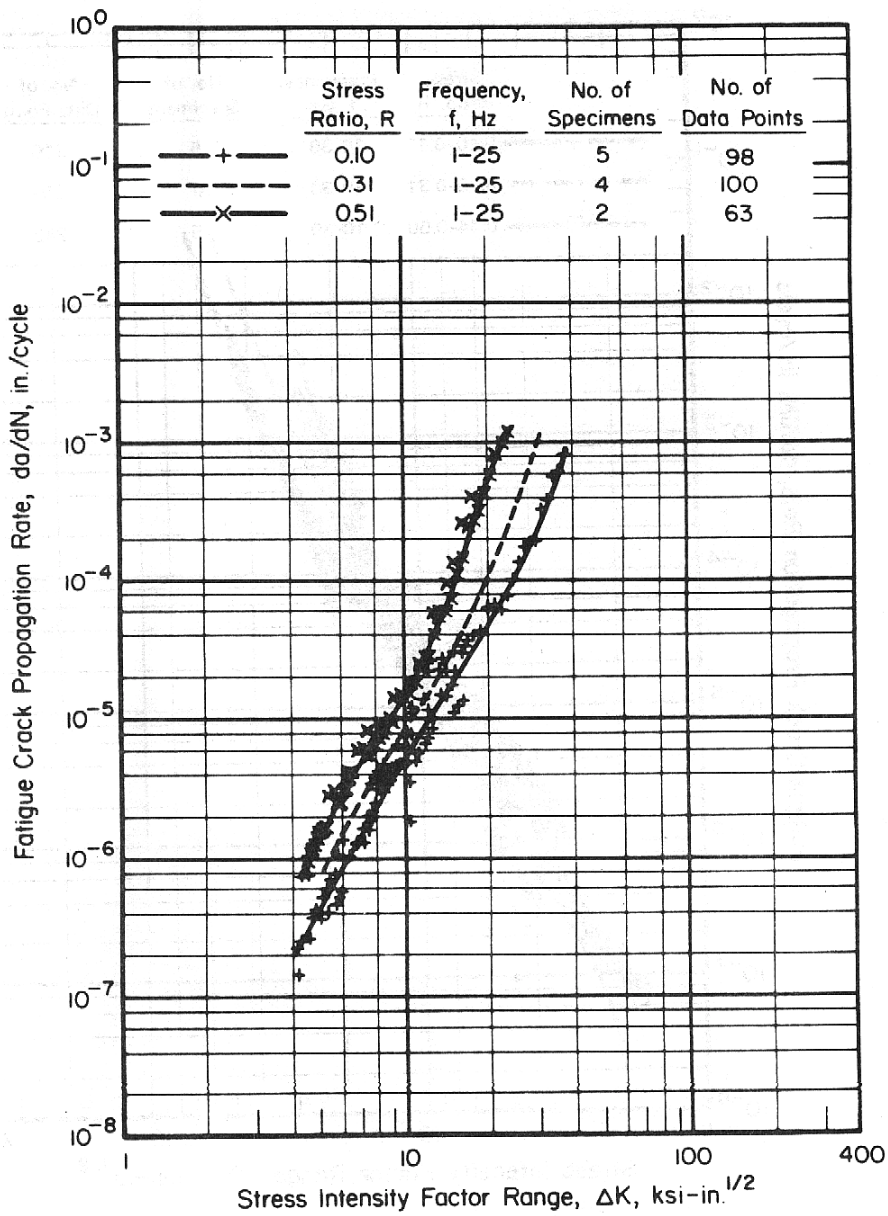

Figure 3.7.6.2.9(c). Fatigue-crack-propagation data for 1.00-inch-thick, 7075-T7351 aluminum alloy plate without buckling restraint [References 3.2.5.1.9(d) and 3.7.6.2.9(a) and (b)].

Specimen Thickness:	*1.00-inch*	*Environment:*	*50% R.H.*
Specimen Width:	*6, 8, 16, 36-inches*	*Temperature:*	*RT*
Specimen Type:	*M(T), C(T)*	*Orientation:*	*L-T*

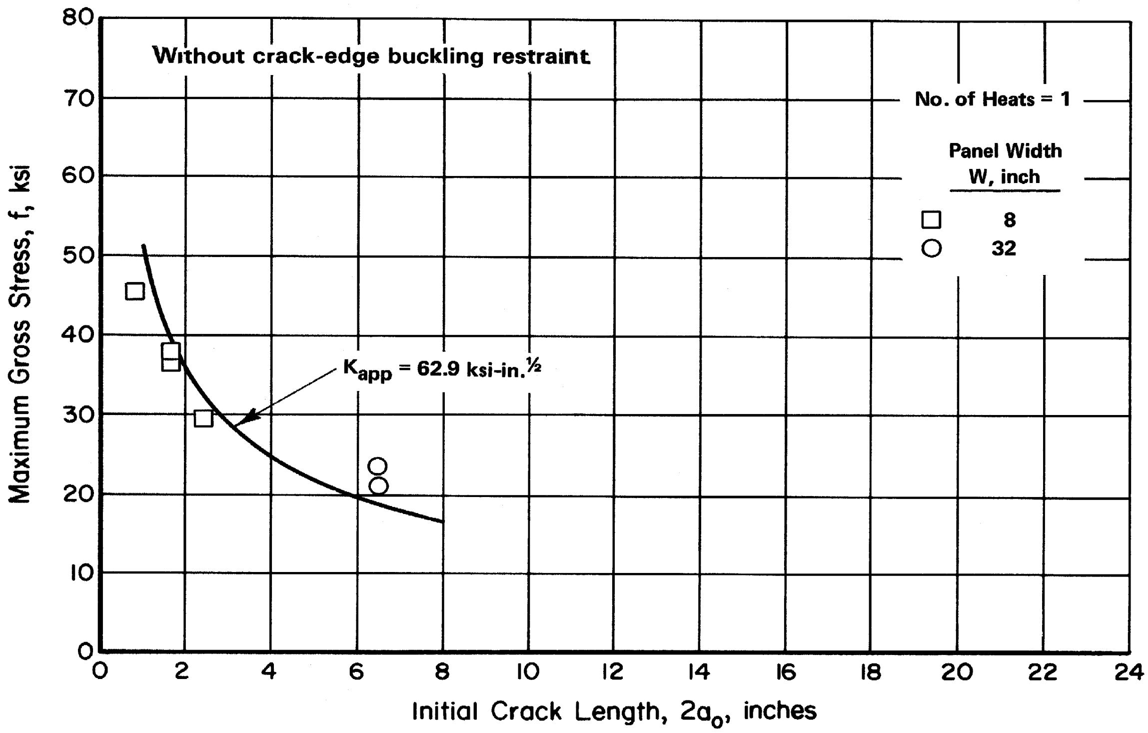

Figure 3.7.6.2.10(a). Residual strength behavior of 0.600-inch-thick 7075-T7351 aluminum alloy plate at room temperature. Crack orientation is L-T [Reference 3.1.2.1.6(g)].

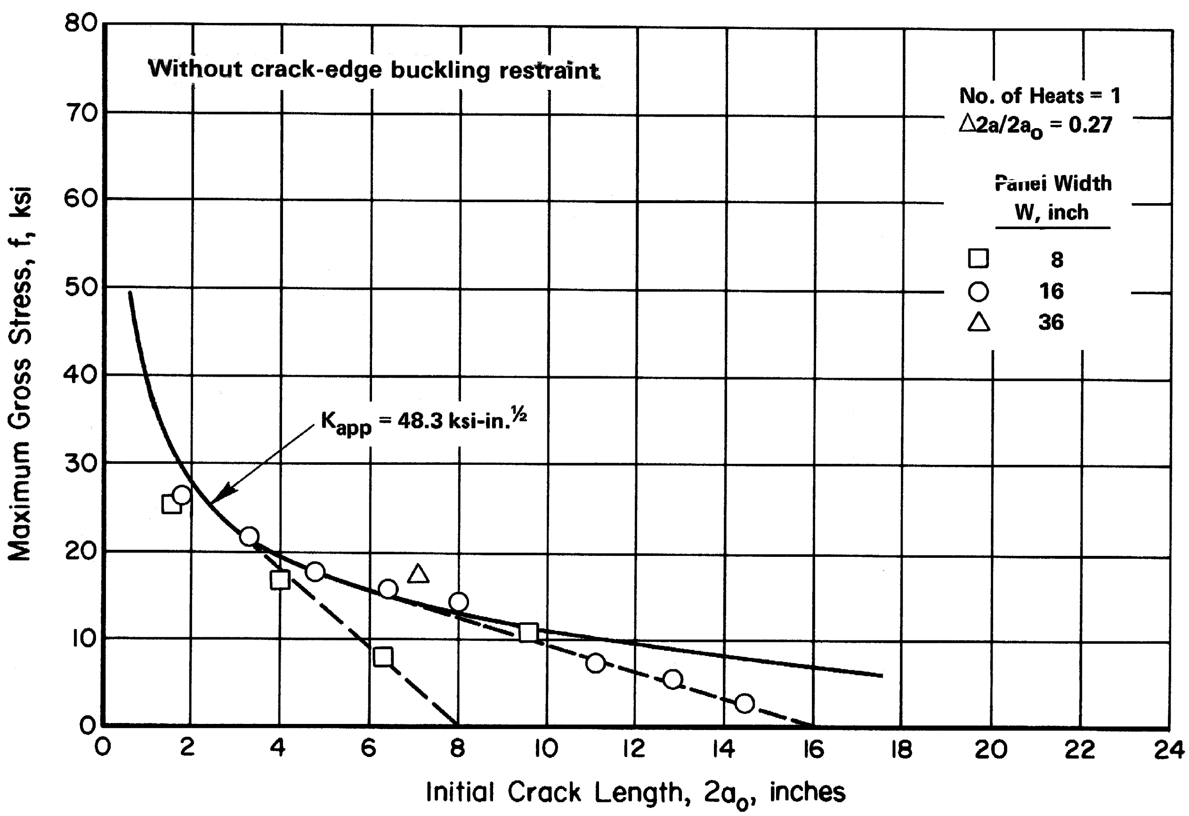

Figure 3.7.6.2.10(b). Residual strength behavior of 1.00-inch-thick 7075-T7351 aluminum alloy plate at room temperature. Crack orientation is L-T [Reference 3.1.2.1.6(j)].

3.7.7 7150 ALLOY

3.7.7.0 *Comments and Properties* — 7150, a second-generation version of 7050, is an Al-Zn-Mg-Cu-Zr alloy developed to provide higher strength properties than 7050 in thicknesses through 3 inches. 7150 is available in the form of plate and extrusion. The T61-type temper provides high strength with guaranteed levels of fracture toughness for plate. The T77-type temper provides high strength with guaranteed toughness and corrosion resistance. The T77-type temper has exfoliation and stress-corrosion resistance comparable to the T76-type temper of the other 7000 series aluminum alloys. Refer to Section 3.1.2.3 for further comments regarding resistance of the alloy to stress-corrosion cracking.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications for 7150 are shown in Table 3.7.7.0(a). Room-temperature mechanical properties are presented in Tables 3.7.7.0(b_1) through (c_2).

Table 3.7.7.0(a). Material Specifications for 7150 Aluminum Alloy

Specification	Form
AMS 4306	Bare plate
AMS 4252	Bare plate
AMS 4307	Extrusion
AMS 4345	Extrusion

The temper index for 7150 is as follows:

Section	Temper
3.7.7.1	T6151 and T61511
3.7.7.2	T7751 and T77511

3.7.7.1 *T6151 and T61511 Tempers* — Figures 3.7.7.1.6(a) and (b) present stress-strain and tangent-modulus curves for bare plate. Figures 3.7.7.1.6(c) and (d) depict stress-strain and tangent-modulus curves for extrusion.

3.7.7.2 *T7751 and T77511 Tempers* — Figures 3.7.7.2.6(a) and (b) present stress-strain and tangent-modulus curves for bare plate. Figures 3.7.7.2.6(c) and (d) depict stress-strain and tangent-modulus curves for extrusion.

Table 3.7.7.0(b_1). Design Mechanical and Physical Properties of 7150 Plate

Specification	AMS 4306			
Form	Plate			
Temper	T6151			
Thickness, in.	0.750-1.000		1.001-1.500	
Basis	A	B	A	B
Mechanical Properties:				
F_{tu}, ksi:				
L	85	87	86	87
LT	84	87	85	86
F_{ty}, ksi:				
L	79	81	80	81
LT	77	79	76	78
F_{cy}, ksi:				
L	77	80	75	77
LT	81	83	80	82
F_{su}, ksi	45	47	46	46
F_{bru}[a], ksi:				
(e/D = 1.5)	121	125	123	124
(e/D = 2.0)	155	160	156	158
F_{bry}[a], ksi:				
(e/D = 1.5)	102	105	101	104
(e/D = 2.0)	119	122	118	121
e, percent (S-basis):				
L	9	...	9	...
LT	9	...	9	...
E, 10^3 ksi	10.2			
E_c, 10^3 ksi	10.6			
G, 10^3 ksi	3.9			
μ	0.33			
Physical Properties:				
ω, lb/in.^{3}	0.102			
C, Btu/(lb)(°F)	...			

a Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.7.0(b_2). Design Mechanical and Physical Properties of 7150 Plate

Specification	AMS 4252				
Form	Plate				
Temper	T7751				
Thickness, in.	0.250-0.499	0.500-0.749	0.750-1.500	1.501-3.000	
Basis	S	S	S	A	B
Mechanical Properties:					
F_{tu}, ksi:					
L	80	83	84	82	84
LT	80	83	84	82[a]	84
ST	...	...	...	77[a]	81
F_{ty}, ksi:					
L	74	77	78	76	78
LT	74	76	77	75[a]	77
ST	...	...	...	67[a]	71
F_{cy}, ksi:					
L	74	76	77	75	77
LT	77	79	81	79	82
F_{su}, ksi	46	47	48	47	48
F_{bru}[b], ksi:					
(e/D = 1.5)	119	124	125	122	125
(e/D = 2.0)	154	160	162	158	162
F_{bry}[b], ksi:					
(e/D = 1.5)	102	105	106	104	108
(e/D = 2.0)	117	120	121	118	123
e, percent: (S-basis)					
L	8	8	8	7	
LT	8	8	8	6	
ST	...	...	...	1	
E, 10^3 ksi	10.3				
E_c, 10^3 ksi	10.7				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb./in.^{3}	0.102				
C, K, and α	...				

a S-basis values. The rounded T_{99} values are as follows: F_{tu}(LT)=83 ksi, F_{tu}(ST)=78 ksi, F_{ty}(LT)=76 ksi, F_{ty}(ST)=68 ksi.
b Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.

Table 3.7.7.0(c_1). Design Mechanical and Physical Properties of 7150 Aluminum Alloy Extrusion

Specification	AMS 4307					
Form	Extrusion					
Temper	T61511					
Thickness or Diameter,[a] in	0.250-0.499	0.500-0.749	0.750-0.999	1.000-1.499		1.500-2.000
Basis	S	S	S	A	B	S
Mechanical Properties:						
F_{tu}, ksi:						
L	87	88	89	89	94	89
LT	80	79	79	85	86	74
F_{ty}, ksi:						
L	82	83	84	83	88	84
LT	73	73	73	77	78	68
F_{cy}, ksi:						
L	80	81	82	82	87	84
LT	80	80	80	77	81	75
F_{su}, ksi	44	45	45	44	46	42
F_{bru}[b], ksi:						
(e/D = 1.5)	119	120	120	118	125	116
(e/D = 2.0)	152	153	154	152	161	150
F_{bry}[b], ksi:						
(e/D = 1.5)	100	100	100	96	102	94
(e/D = 2.0)	118	120	120	117	124	117
e, percent (S-basis):						
L	8	9	8	8	...	8
E, 10^3 ksi	10.4					
E_c, 10^3 ksi	11.0					
G, 10^3 ksi	4.0					
μ	0.33					
Physical Properties:						
ω, lb/in.^{3}	0.102					
C, K, and α	...					

a The mechanical properties are to be based upon the thickness at the time of quench.
b Bearing values are “dry pin” values per Section 1.4.7.1.

Table 3.7.7.0(c_2). Design Mechanical and Physical Properties of 7150 Aluminum Alloy Extrusion

Specification	AMS 4345					
Form	Extrusion					
Temper	T77511					
Cross-Sectional Area, in²	≤20					
Thickness or Diameter,[a] in.	≤0.249		0.250-0.499		0.500-0.749	0.750-2.000
Basis	A	B	A	B	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	85[b]	88	87[c]	89	88	89
LT	81	84	82[c]	86	83	83
F_{ty}, ksi:						
L	78[b]	83	82[c]	84	83	84
LT	74	79	76[c]	79	79	78
F_{cy}, ksi:						
L	78[b]	82	82[c]	85	83	84
LT	76	81	80	82	81	82
F_{su}, ksi	44	46	45	46	46	46
F_{bru}[d], ksi:						
(e/D = 1.5)	122	126	124	127	125	123
(e/D = 2.0)	158	163	161	165	162	159
F_{bry}[d], ksi:						
(e/D = 1.5)	100	106	105	108	106	108
(e/D = 2.0)	118	125	124	127	125	127
e, percent (S-Basis):						
L	7	...	8	...	9	8
E, 10^3 ksi	10.4					
E_c, 10^3 ksi	10.9					
G, 10^3 ksi	4.0					
μ	0.33					
Physical Properties:						
ω, lb/in.³	0.102					
C, K, and α	...					

a The mechanical properties are to be based upon the thickness at the time of quench.
b S basis. The rounded T_{99} values for F_{tu},(L)= 87 ksi, for F_{ty}(L) = 81 ksi, and for F_{cy}(L) = 79ksi.
c S basis. The rounded T_{99} values for F_{tu}(L) = 88 ksi, for F_{tu}(LT) = 84 ksi, for F_{ty} (L) = 82 ksi, for F_{ty} (LT) = 77 ksi, and for F_{cy} (L) = 82 ksi.
d Bearing values are "dry pin" values per Section 1.4.7.1.

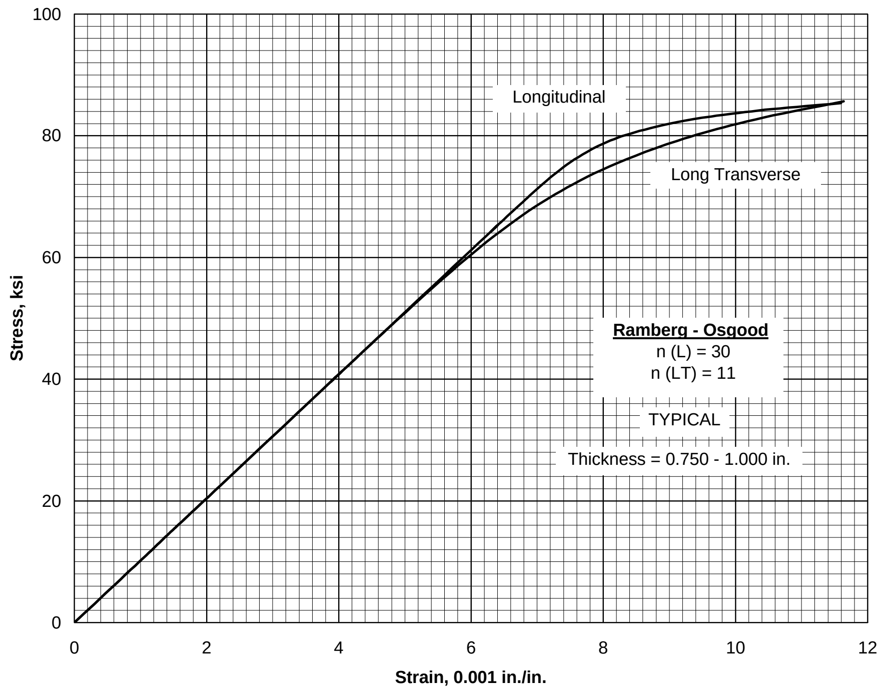

Figure 3.7.7.1.6(a). Typical tensile stress-strain curves for 7150-T6151 aluminum alloy plate at room temperature.

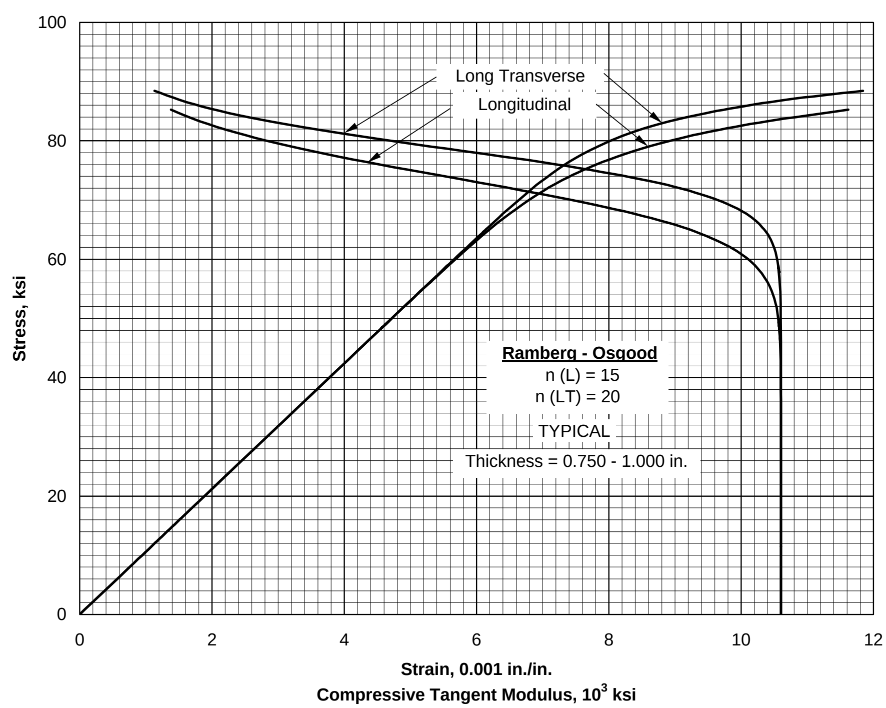

Figure 3.7.7.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7150-T6151 aluminum alloy plate at room temperature.

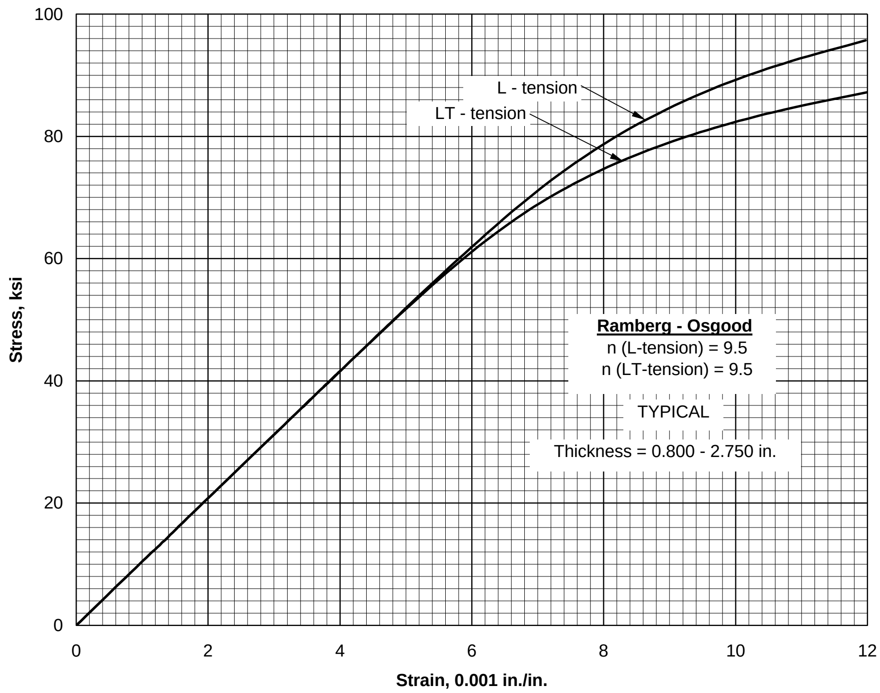

Figure 3.7.7.1.6(c). Typical tensile stress-strain curves for 7150-T61511 aluminum alloy extrusion at room temperature.

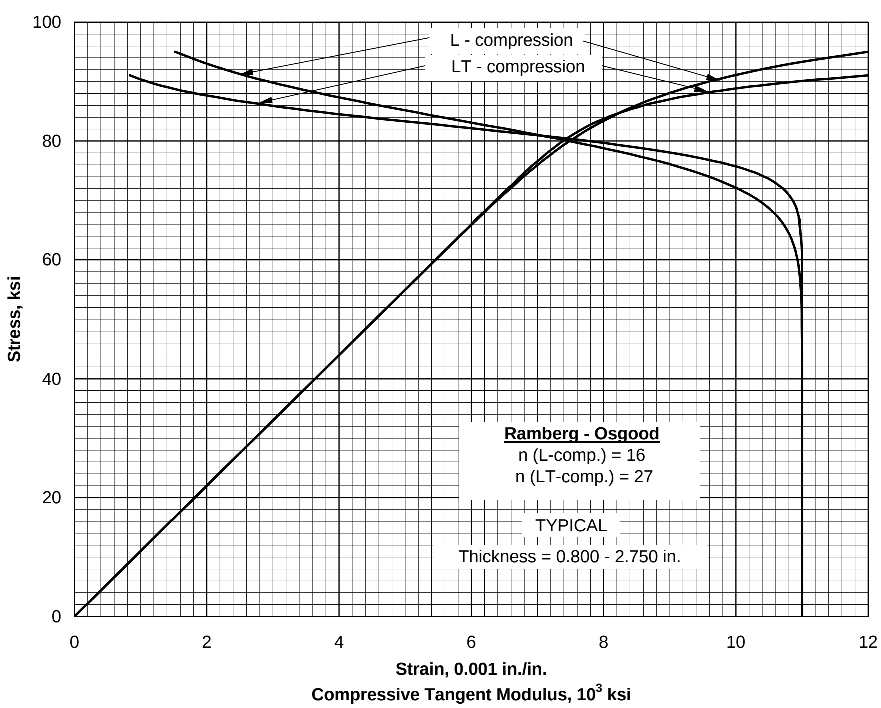

Figure 3.7.7.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7150-T61511 aluminum alloy extrusion at room temperature.

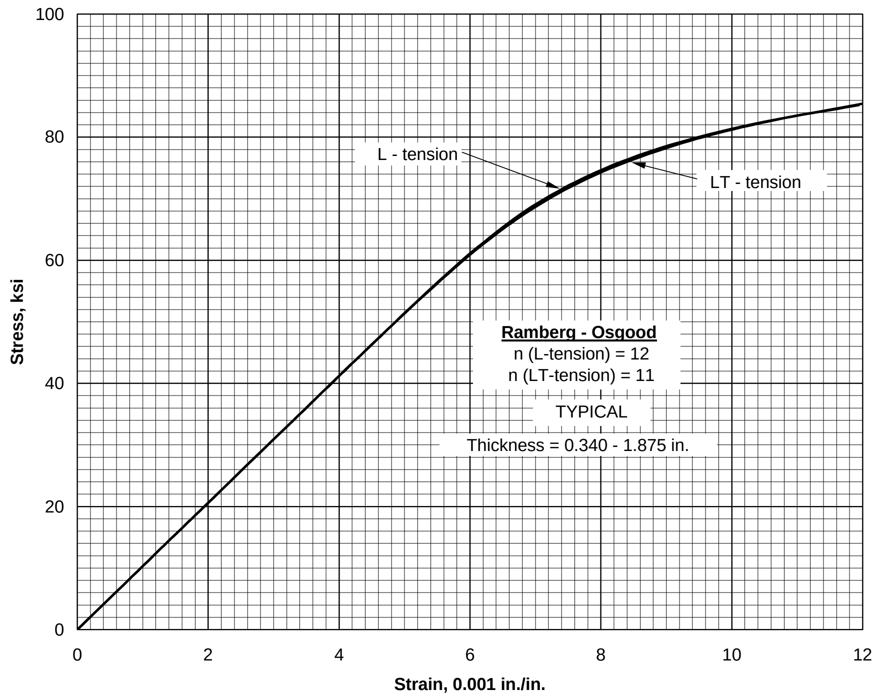

Figure 3.7.7.2.6(a). Typical tensile stress-strain curves for 7150-T7751 aluminum alloy plate at room temperature.

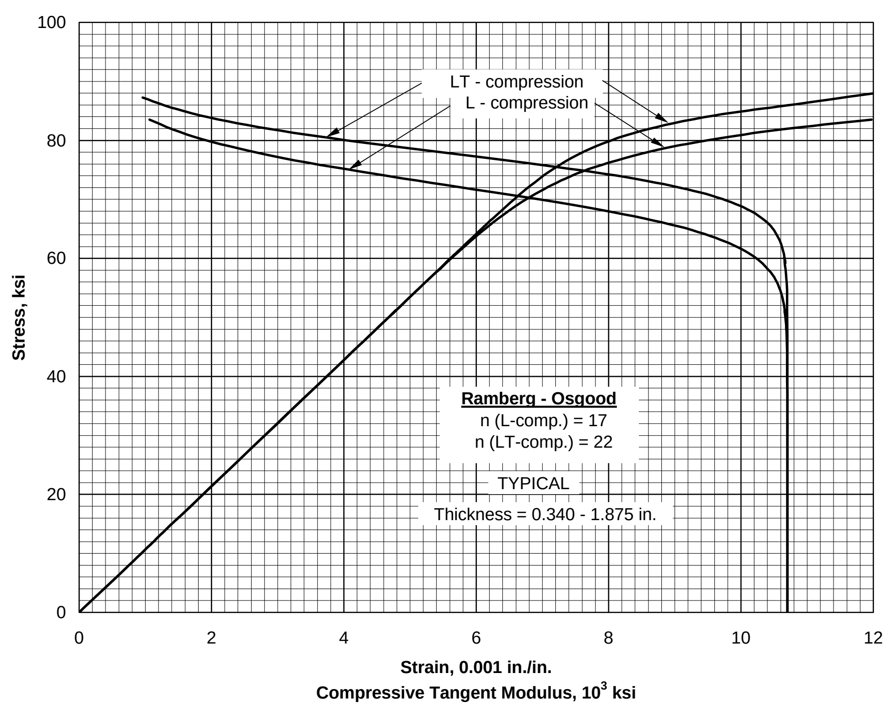

Figure 3.7.7.2.6(b). Typical compressive stress-strain and tangent-modulus curves for 7150-T7751 aluminum alloy plate at room temperature.

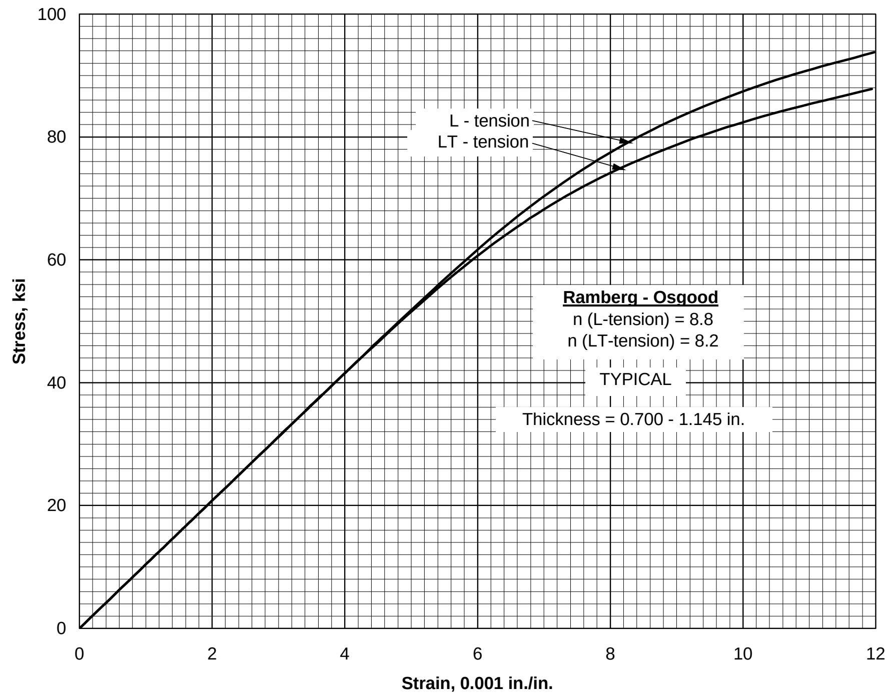

Figure 3.7.7.2.6(c). Typical tensile stress-strain curves for 7150-T77511 aluminum alloy extrusion at room temperature.

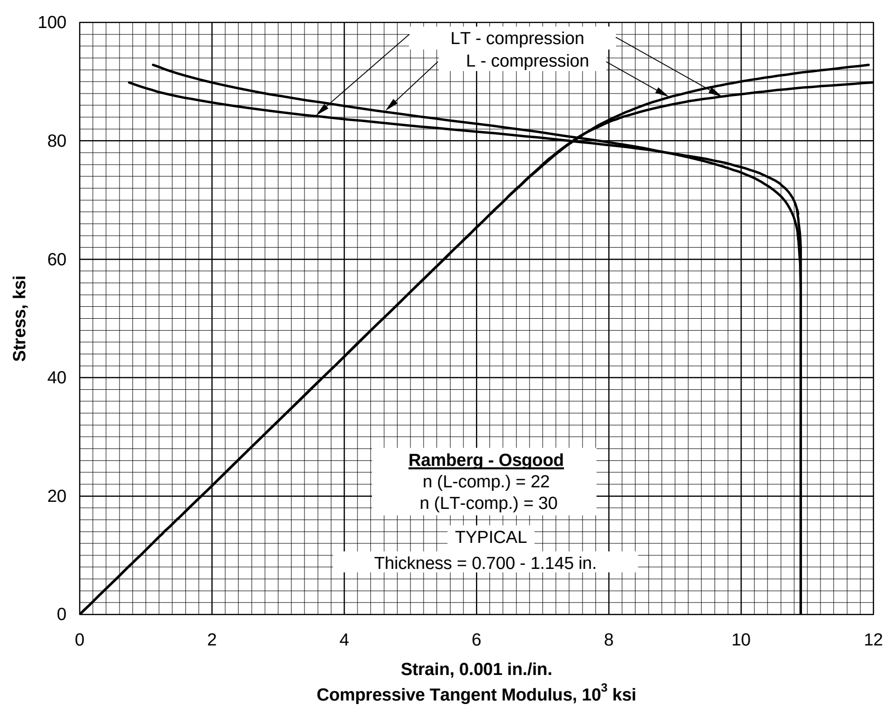

Figure 3.7.7.2.6(d). Typical compressive stress-strain and tangent-modulus curves for 7150-T77511 aluminum alloy extrusion.

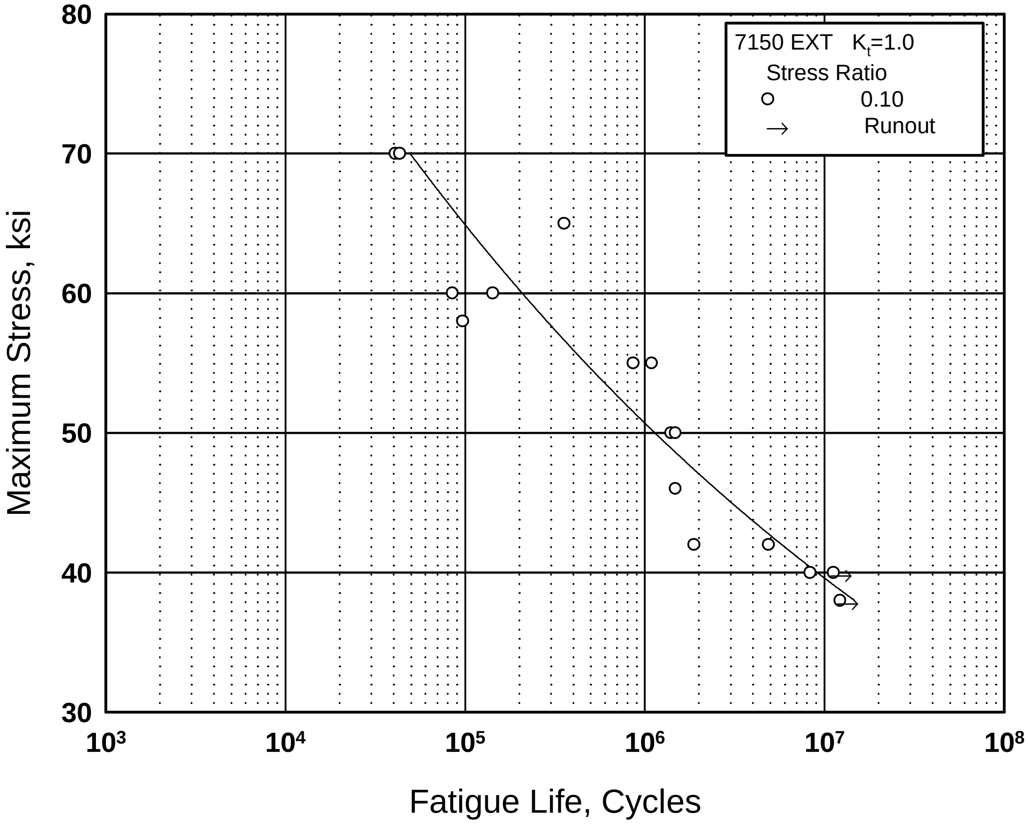

Figure 3.7.7.2.8(a). Best-fit S/N curves for unnotched 7150-T77511 aluminum alloy extrusion, longitudinal orientation.

Correlative Information for Figure 3.7.7.2.8(a).

Product Forms: Extruded shape, 1.125-inch, 1.45-inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
89	84	RT

Specimen Details: Unnotched
Round, 0.3-inch diameter, removed from center of section

Surface Condition: Polished to 10 micro-inch or better

Reference: 3.7.7.2.8

Test Parameters:
Loading - Axial
Frequency - 25 Hz
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Fatigue Life Equation:
Log N_f = 21.89 - 9.32 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.321
Standard Deviation, Log (Life) = 0.753
R^2 = 81.8%

Sample Size: 16

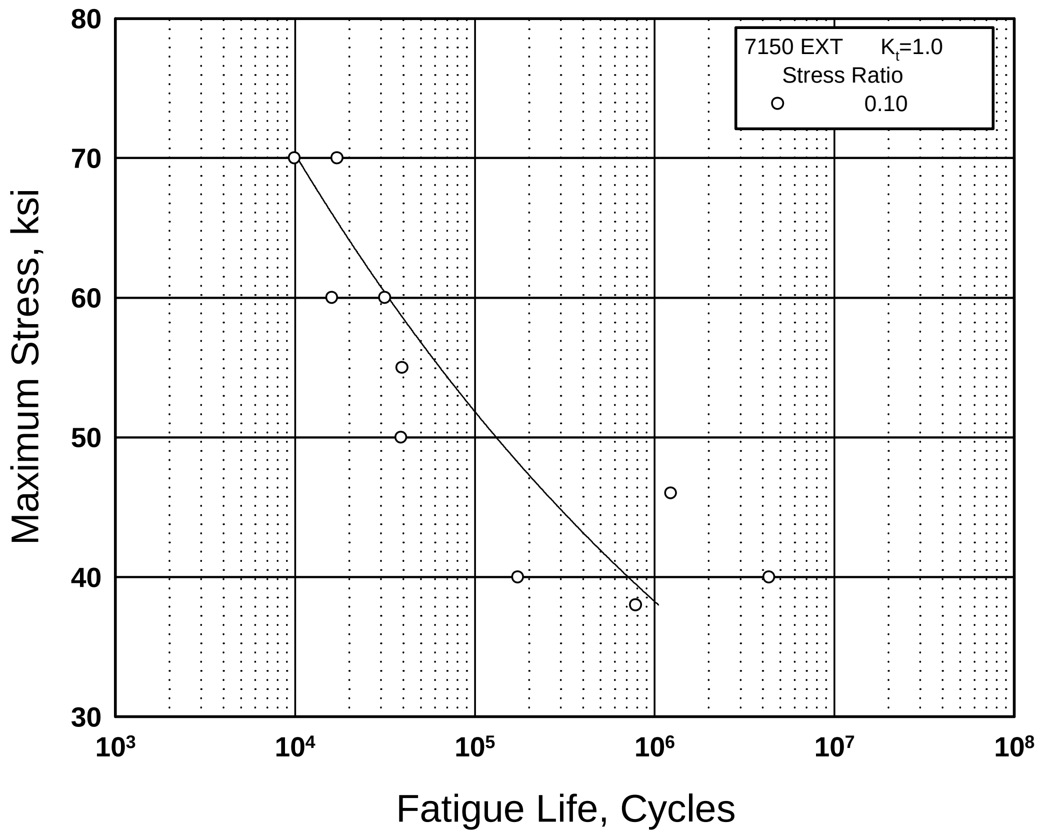

Figure 3.7.7.2.8(b). Best-fit S/N curves for unnotched 7150-T77511 aluminum alloy extrusion, long transverse orientation.

Correlative Information for Figure 3.7.7.2.8(b).

Product Forms: Extruded shape, 1.125-inch, 1.45-inch

Properties:

TUS, ksi	TYS, ksi	Temp., °F
83	78	RT

Specimen Details: Unnotched
Round, 0.3-inch diameter, removed from center of section

Surface Condition: Polished to 10 micro-inch or better

Reference: 3.7.7.2.8

Test Parameters:
Loading - Axial
Frequency - 25 Hz
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Fatigue Life Equation:
Log N_f = 17.98 - 7.57 log (S_{max})
Std. Error of Estimate, Log (Life) = 22.53(1/S_{max})
Standard Deviation, Log (Life) = 0.977
R^2 = 74.4 %

Sample Size: 10

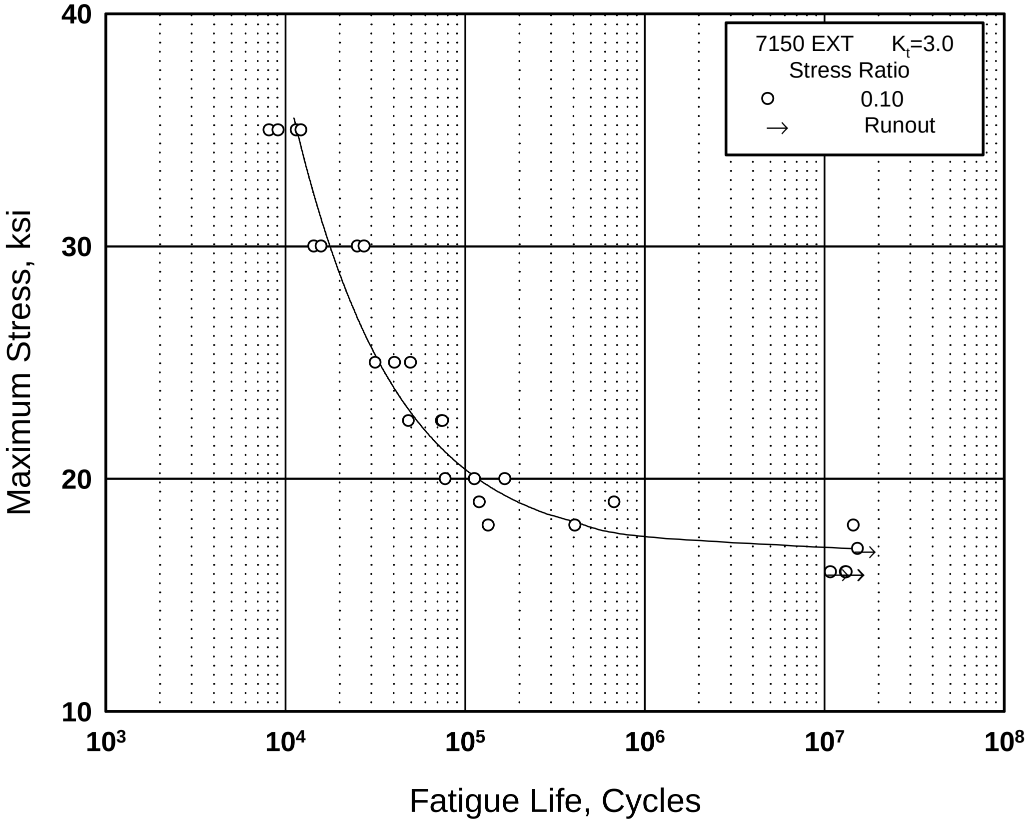

Figure 3.7.7.2.8(c). Best-fit S/N curves for notched, K_t = 3.0, 7150-T77511 aluminum alloy extrusion, longitudinal and long transverse orientations.

<u>Correlative Information for Figure 3.7.7.2.8(c).</u>

<u>Product Forms:</u> Extruded shape, 1.125-inch, 1.45-inch

<u>Properties:</u>	<u>TUS, ksi</u>	<u>TYS, ksi</u>	<u>Temp., °F</u>
Longitudinal	89	84	RT
Long Transverse	83	78	RT

<u>Specimen Details:</u> Circumferentially notched, K_t = 3.0 round, 0.253-inch net diameter, 0.013-inch root radius, removed from center of section

<u>Surface Condition:</u> Notch

<u>Reference:</u> 3.7.7.2.8

<u>Test Parameters:</u>
Loading - Axial
Frequency - 25 Hz
Temperature - RT
Environment - Air

<u>No. of Heats/Lots:</u> 2

<u>Fatigue Life Equation:</u>
Log N_f = 5.71 - 1.31 log (S_{max} - 16.92)
Std. Error of Estimate, Log (Life) = 4.51 (1/S_{max})
Standard Deviation, Log (Life) = 0.750
R^2 = 92.4%

<u>Sample Size:</u> 25

3.7.8 7175 ALLOY

3.7.8.0 ***Comments and Properties*** — 7175 is a high-purity, high-strength Al-Zn-Mg-Cu alloy. In the form of die forgings the alloy is available in the T66, T74, and T7452 tempers. Die forgings of 7175-T66 develop higher static strength than 7075-T6 forgings with fatigue, fracture, and stress-corrosion properties about equivalent to those of 7075-T6 forgings. 7175-T74-type die and hand forgings develop static strengths about equivalent to those of 7075-T6 forgings, with toughness and fatigue properties equal or superior to those of 7075-T73 forgings. The T74-type temper provides stress-corrosion resistance and strength characteristics intermediate to those of T76 and T73 in 7075. Refer to Section 3.1.2.3 for comments regarding the resistance of the alloy to stress-corrosion cracking, and to Section 3.1.3.4 for comments regarding the weldability of the alloy.

The properties of extrusions should be based upon the thickness at the time of quenching prior to machining. Selection of the mechanical properties based upon its final machined thickness may be unconservative; therefore, the thickness at the time of quenching to achieve properties is an important factor in the selection of the proper thickness column. For extrusions having sections with various thicknesses, consideration should be given to the properties as a function of thickness.

Material specifications for 7175 are presented in Table 3.7.8.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.7.8.0(b) through (d).

Table 3.7.8.0(a). Material Specifications for 7175 Aluminum Alloy

Specification	Form
AMS 4148	Die forging
AMS 4149	Die and hand forging
AMS 4179	Hand forging
AMS-A-22771	Forging
AMS 4344	Extrusion

The temper index for 7175 is as follows:

Section	Temper
3.7.8.1	T73511
3.7.8.2	T74 and T7452 (formerly T736 and T73652)

3.7.8.1 ***T73511 Temper*** — Figures 3.7.8.1.6(a) and (b) show tensile and compressive stress-strain and tangent-modulus curves for extrusion. Figures 3.7.8.1.8(a) through (d) present fatigue curves for extrusion.

3.7.8.2 ***T74 and T7452 Tempers*** — Figures 3.7.8.2.6(a) through (f) present tensile and compressive stress-strain and tangent-modulus curves for die and hand forging. Figures 3.7.8.2.8(a) and (b) present fatigue curves for die and hand forging.

Table 3.7.8.0(b). Design Mechanical and Physical Properties of 7175 Aluminum Alloy Die Forging

Specification	AMS 4148	AMS 4149						
Form	Die forging							
Temper	T66	T74[a,b]						
Thickness, in.	≤3.000	<1.000	1.001-2.000		2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	A	B	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	86	76	74	77	76	73	70	68
T[c]	77	71	71[d]	...	71	70	68	65
F_{ty}, ksi:								
L	76	66	64	67	66	63	61	58
T[c]	66	62	62[d]	...	62	60	58	55
F_{cy}, ksi:								
L	...	67	65	68	67	...	...	...
ST	...	63	61	64	63	...	...	...
F_{su}, ksi	...	43	42	44	43	...	...	...
F_{bru}[e], ksi:								
(e/D = 1.5)	...	106	105	109	106	...	...	...
(e/D = 2.0)	...	140	137	142	140	...	...	...
F_{bry}[e], ksi:								
(e/D = 1.5)	...	86	84	88	86	...	...	...
(e/D = 2.0)	...	102	99	103	102	...	...	...
e, percent (S-basis):								
L	7	7	7	...	7	7	7	7
T[c]	4	4	4	...	4	4	4	4
E, 10^3 ksi	10.2							
E_c, 10^3 ksi	10.7							
G, 10^3 ksi	3.9							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.101							
C, Btu/(lb)(°F)	0.23 (at 212°F)							
K, Btu/[(hr)(ft^2)(°F)/ft]	76 (at 77°F for T66); 90 (at 77°F for T736)							
α, 10^{-6} in./in./°F	12.9 (68 to 212°F)							

a When die forgings are machined before heat treatment, section thickness at time of heat treatment shall determine minimum mechanical properties as long as original (as-forged) thickness does not exceed maximum thickness for the alloy as shown in the table.

b Design allowables were based upon data obtained from testing die forgings, heat treated by suppliers, and supplied in T74 temper.

c T indicates any grain direction not within ±15° of being parallel to the forging flow lines. F_{cy}(T) values are based upon short transverse (ST) test data.

d Specification value. T tensile properties are presented on an S basis only.

e Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.8.0(c_1). Design Mechanical and Physical Properties of 7175 Aluminum Alloy Hand Forging

Specification	AMS 4149 and AMS-A-22771				
Form	Hand forging				
Temper	T74				
Thickness or Diameter[a,b], in.	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	73	73	71	68	65
LT	71	71	70	67	64
ST	...	69	68	66	63
F_{ty}, ksi:					
L	63	63	61	57	54
LT	60	60	58	56	52
ST	...	60	57	55	52
F_{cy}, ksi:					
L	63	63	61	59	55
LT	62	63	61	60	56
ST	61	62	60	59	55
F_{su}, ksi:					
L	43	43	43	41	39
LT	42	42	41	39	38
ST	42	42	41	39	38
F_{bru}[c], ksi:					
(e/D = 1.5)	106	106	104	100	95
(e/D = 2.0)	138	138	136	131	125
F_{bry}[c], ksi:					
(e/D = 1.5)	73	78	80	81	76
(e/D = 2.0)	89	94	95	95	90
e, percent:					
L	9	9	9	8	8
LT	5	5	5	5	5
ST	...	4	4	4	4
E, 10^3 ksi	10.2				
E_c, 10^3 ksi	10.6				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.101				
C, Btu/(lb)(°F)	0.23 (at 212°F)				
K, Btu/[(hr)(ft^2)(°F)/ft]	90 (at 77°F)				
α 10^{-6} in./in./°F	12.9 (68 to 212°F)				

a When hand forgings are machined before heat treatment, the section thickness at time of heat treatment shall determine the minimum mechanical properties as long as the original (as-forged) thickness does not exceed the maximum thickness for the alloy as shown in the table.
b The maximum cross-sectional area of hand forgings in 256 sq. in.
c Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.8.0(c_2). Design Mechanical and Physical Properties of 7175 Aluminum Alloy Hand Forging

Specification	AMS 4149 and AMS-A-22771				
Form	Hand forging				
Temper	T7452				
Thickness or Diameter[a], in.	1.001-2.000	2.001-3.000	3.001-4.000	4.001-5.000	5.001-6.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	71	71	68	65	63
LT	69	69	67	64	61
ST	...	67	65	63	60
F_{ty}, ksi:					
L	61	61	57	54	51
LT	58	58	55	52	49
ST	...	54	51	49	46
F_{cy}, ksi:					
L	58	58	55	52	49
LT	61	61	57	54	50
ST	60	60	57	54	51
F_{su}, ksi:					
L	38	39	39	38	37
LT	38	39	38	38	36
ST	40	41	40	39	38
F_{bru}[b], ksi:					
(e/D = 1.5)	102	102	99	95	90
(e/D = 2.0)	133	133	130	124	118
F_{bry}[b], ksi:					
(e/D = 1.5)	80	82	80	76	72
(e/D = 2.0)	95	98	95	92	87
e, percent:					
L	9	9	9	8	8
LT	5	5	5	5	5
ST	...	4	4	4	4
E, 10^3 ksi	10.2				
E_c, 10^3 ksi	10.5				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.101				
C, Btu/(lb)(°F)	0.23 (at 212°F)				
K, Btu/[(hr)(ft^2)(°F)/ft]	90 (AT 77°F)				
α, 10^{-6} in./in./°F	12.9 (68 to 212°F)				

a The maximum cross-sectional area of hand forgings is 256 sq.in.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.8.0(d). Design Mechanical and Physical Properties of 7175 Aluminum Alloy Extrusion

Specification	AMS 4344	
Form	Extrusion	
Condition	T73511	
Cross-Sectional Area, in^2	32-65	
Thickness or Diameter,[a] in.	0.250-0.999	1.000-2.000
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	69	69
LT	63	63
F_{ty}, ksi:		
L	59	59
LT	52	52
F_{cy}, ksi:		
L	...	59
LT	...	59
F_{su}, ksi	...	40
F_{bru}[b], ksi:		
(e/D = 1.5)	...	97
(e/D = 2.0)	...	125
F_{bry}[b], ksi:		
(e/D = 1.5)	...	79
(e/D = 2.0)	...	95
e, percent:		
L	...	8
LT	...	4
E, 10^3 ksi	10.1	
E_c, 10^3 ksi	10.5	
G, 10^3 ksi	3.9	
μ	0.33	
Physical Properties:		
ω, lb/in.^{3}	0.101	
C, Btu/(lb)(°F)	0.23 (at 212°F)	
K, Btu/[(hr)(ft^2)(°F)/ft]	...	
α, 10^{-6} in./in./°F	12.9 (68 to 212°F)	

a The mechanical properties are to be based upon the thickness at the time of quench.
b Bearing values are "dry pin" values per Section 1.4.7.1.

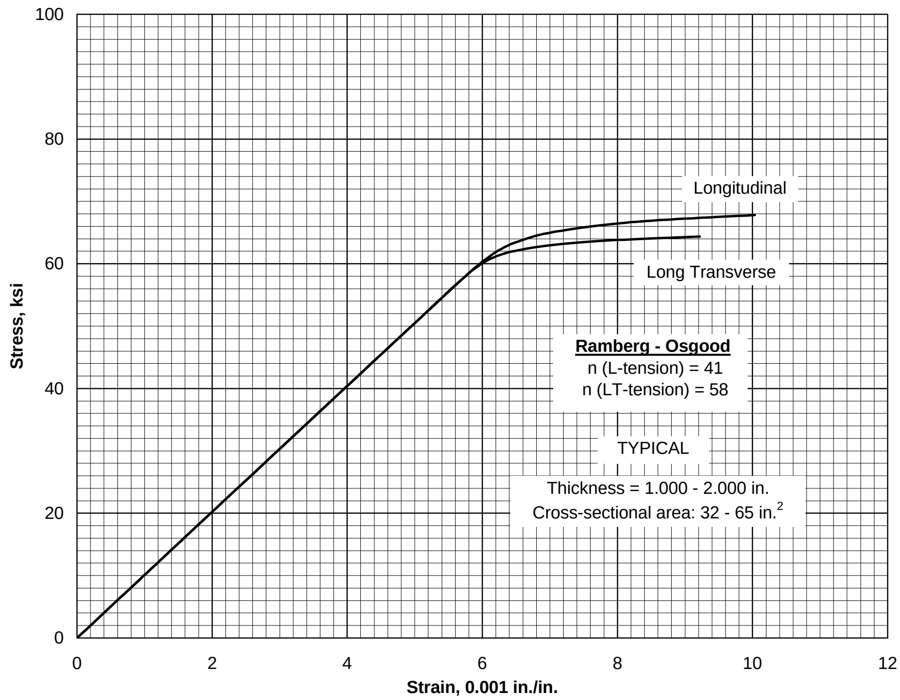

Figure 3.7.8.1.6(a). Typical tensile stress-strain curves for aluminum alloy 7175-T73511 extrusion at room temperature.

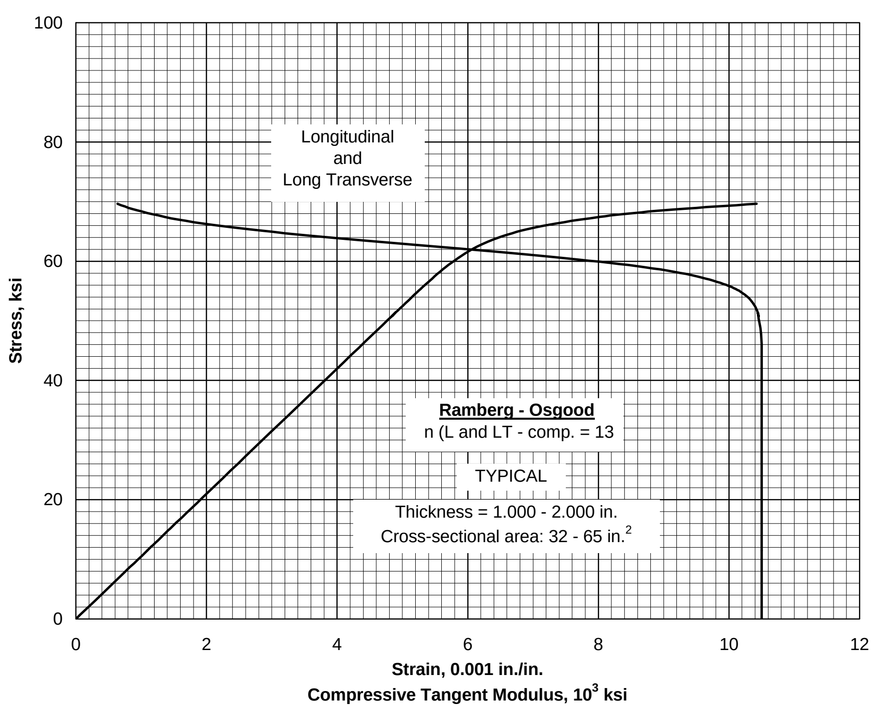

Figure 3.7.8.1.6(b). Typical compressive stress-strain and tangent-modulus curves for aluminum alloy 7175-T73511 extrusion at room temperature.

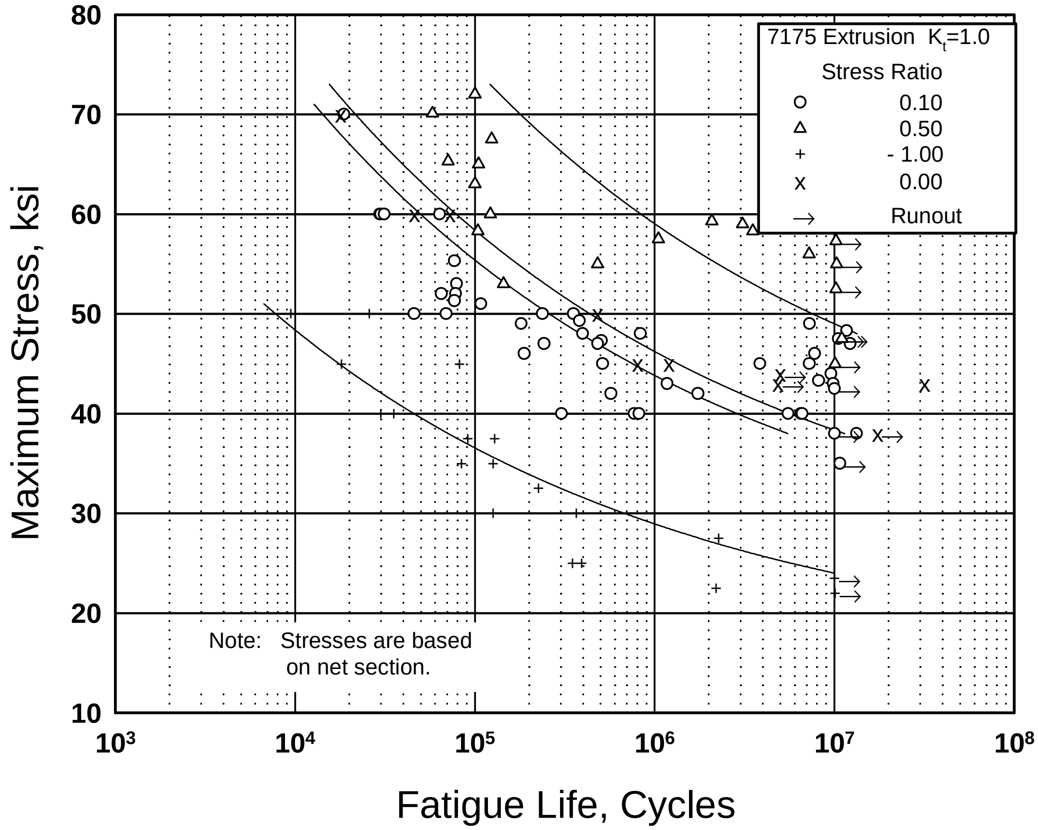

Figure 3.7.8.1.8(a). Best-fit S/N curves for unnotched 7175-T73511 alloy extrusion, longitudinal direction.

Correlative Information for Figure 3.7.8.1.8(a)

Product Form: Extrusion 1.8-inch thick, extruded round, 3-3/4-inch diameter, extruded rectangle, 2-1/2 x 5-inch thick, extrusion, unspecified size

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	76	67	70

Specimen Details: 0.25-inch minimum diameter hourglass gage section 30-inch diameter

Surface Condition: 32 RMS gage section specified

References: 3.7.8.1.8(a), (b), and (c)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - 70°F
Environment - Air

No. of Heats/Lots: 11

Equivalent Stress Equation:
$\text{Log } N_f = 12.01\text{-}5.26 \log (S_{eq})$
$S_{eq} = S_a + 0.32S_m - 15.04$
Std. Error of Estimate, Log (Life) = $18.44(1/S_{eq})$
Standard Deviation, Log (Life) = 1.35
$R^2 = 58\%$

Sample Size = 96

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

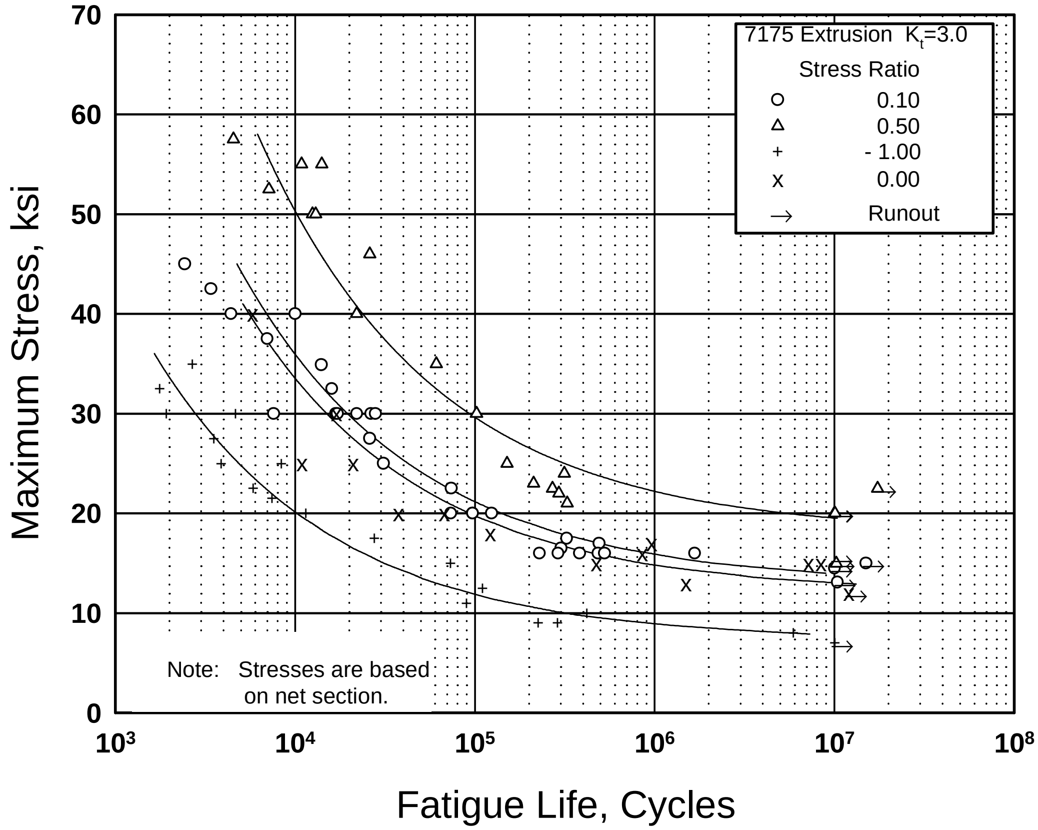

Figure 3.7.8.1.8(b). Best-fit S/N curves for notched, K_t = 3.0, 7175-T73511 alloy extrusion, longitudinal direction.

Correlative Information for Figure 3.7.8.1.8(b)

Product Form: Extrusion 1.8-inch thick, extruded round, 3-3/4-inch diameter, extruded rectangle, 2-1/2 x 5-inch thick, extrusion, unspecified size

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	76	67	70

Specimen Details: Circumferential notch, K_t = 3
0.5-inch gross diameter
0.36-inch net diameter
0.0005-inch notch radius
Circumferential 60° V notch

References: 3.7.8.1.8(a), (b), and (c)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - 70°F
Environment - Air

No. of Heats/Lots: 11

Equivalent Stress Equation:
Log N_f = 6.50-2.25 log (S_{eq})
$S_{eq} = S_a + 0.20S_m - 7.21$
Std. Error of Estimate, Log (Life) = 3.92(1/S_{eq})
Standard Deviation, Log (Life) = 1.51
R^2 = 91%

Sample Size = 86

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

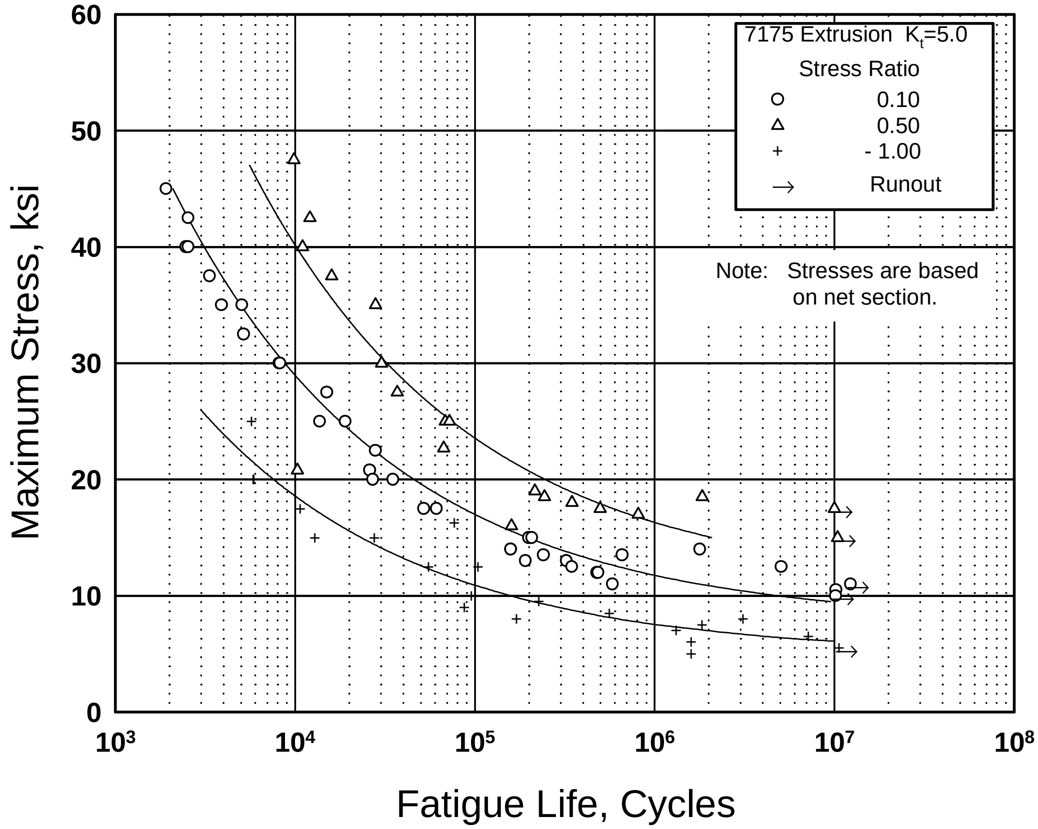

Figure 3.7.8.1.8(c). Best-fit S/N curves for notched, K_t = 5.0, 7175-T73511 alloy extrusion, longitudinal direction.

Correlative Information for Figure 3.7.8.1.8(c)

Product Form: Extrusion 1.8-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
76	67	70

Specimen Details: Circumferential notch, K_t = 5
0.5-inch gross diameter
0.36-inch net diameter
0.0005-inch notch radius

References: 3.7.8.1.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - 70°F
Environment - Air

No. of Heats/Lots: 10

Equivalent Stress Equation:
Log N_f = 7.63-2.78 log (S_{eq}-7.3)
$S_{eq} = S_{max}(1-R)^{0.56}$
Std. Error of Estimate, Log (Life) = 3.71(1/S_{eq})
Standard Deviation, Log (Life) = 1.45
R^2 = 90%

Sample Size = 136

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

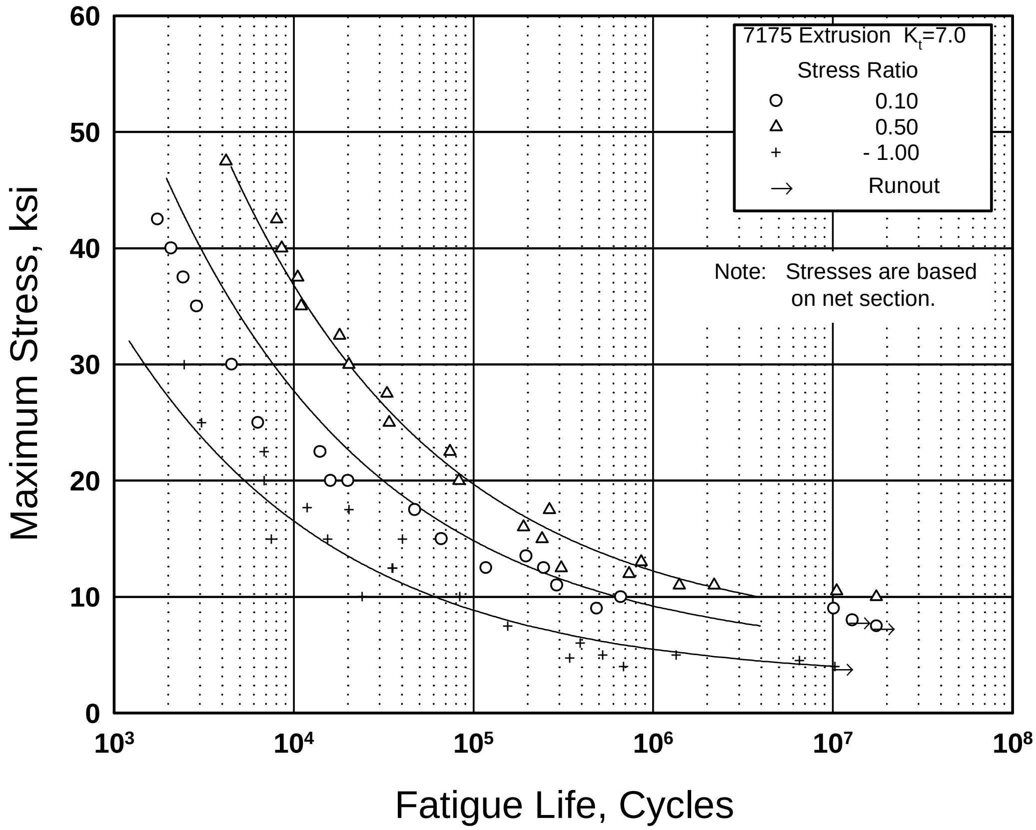

Figure 3.7.8.1.8(d). Best-fit S/N curves for notched, K_t = 7.0, 7175-T73511 alloy extrusion, longitudinal direction.

Correlative Information for Figure 3.7.8.1.8(d)

Product Form: Extrusion 1.8-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
76	67	70

Specimen Details: Circumferential notch, K_t = 7
0.5-inch gross diameter
0.36-inch net diameter
0.0005-inch notch radius

References: 3.7.8.1.8(a) and (b)

Test Parameters:
Loading - Axial
Frequency - Not specified
Temperature - 70°F
Environment - Air

No. of Heats/Lots: 9

Equivalent Stress Equation:
Log N_f = 7.15-2.78 log (S_{eq})
$S_{eq} = S_a + 0.27S_m - 2.88$
Std. Error of Estimate, Log (Life) =
0.11 + 1.60 ($1/S_{eq}$)
Standard Deviation, Log (Life) = 1.55
R^2 = 92%

Sample Size = 63

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

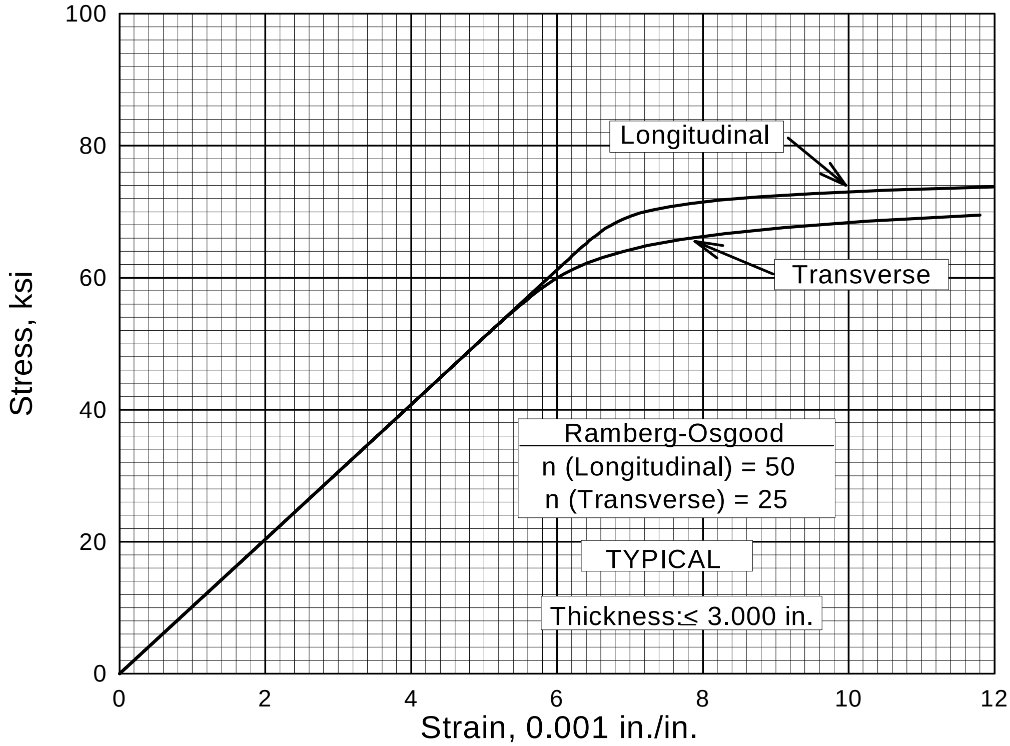

Figure 3.7.8.2.6(a). Typical tensile stress-strain curves for 7175-T74 aluminum alloy die forging at room temperature.

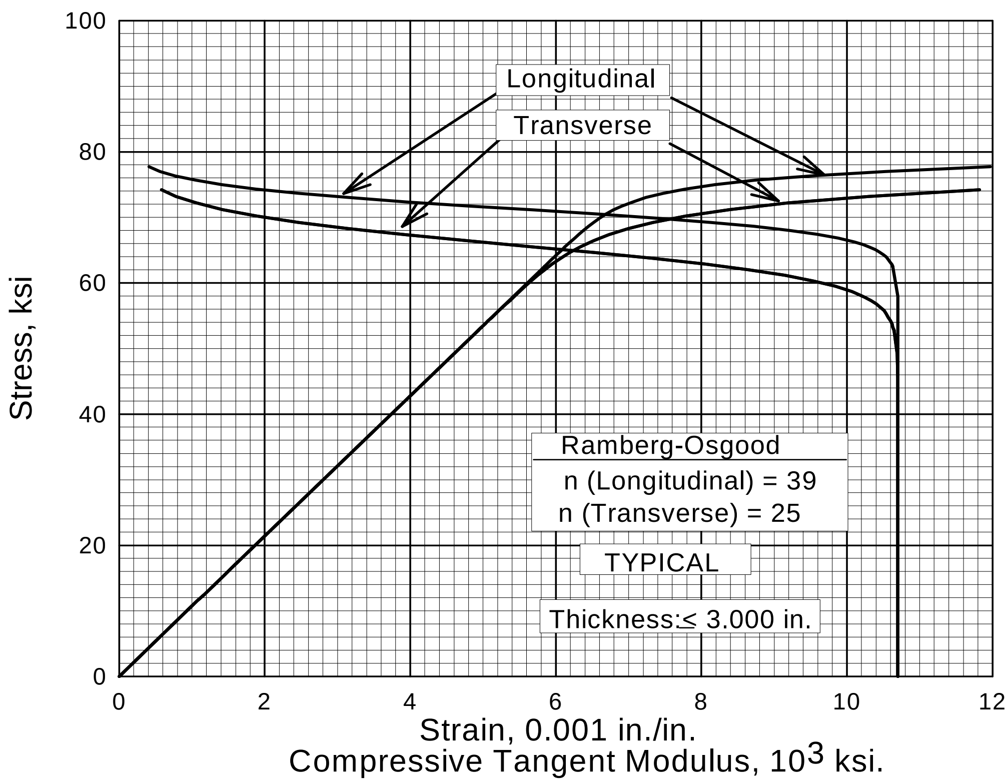

Figure 3.7.8.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7175-T74 aluminum alloy die forging at room temperature.

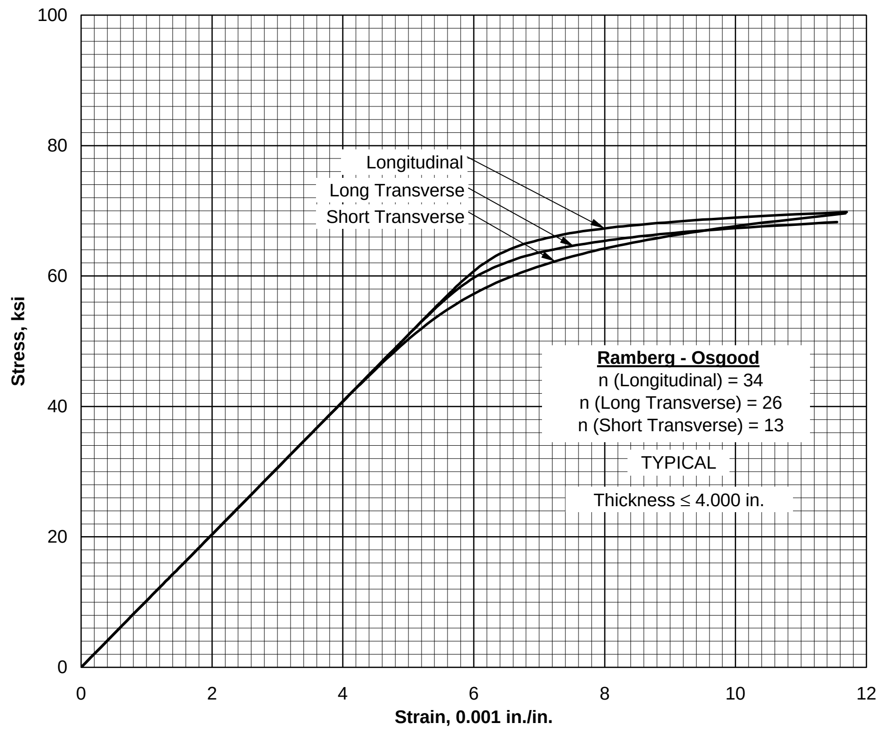

Figure 3.7.8.2.6(c). Typical tensile stress-strain curves for 7175-T74 aluminum alloy hand forging at room temperature.

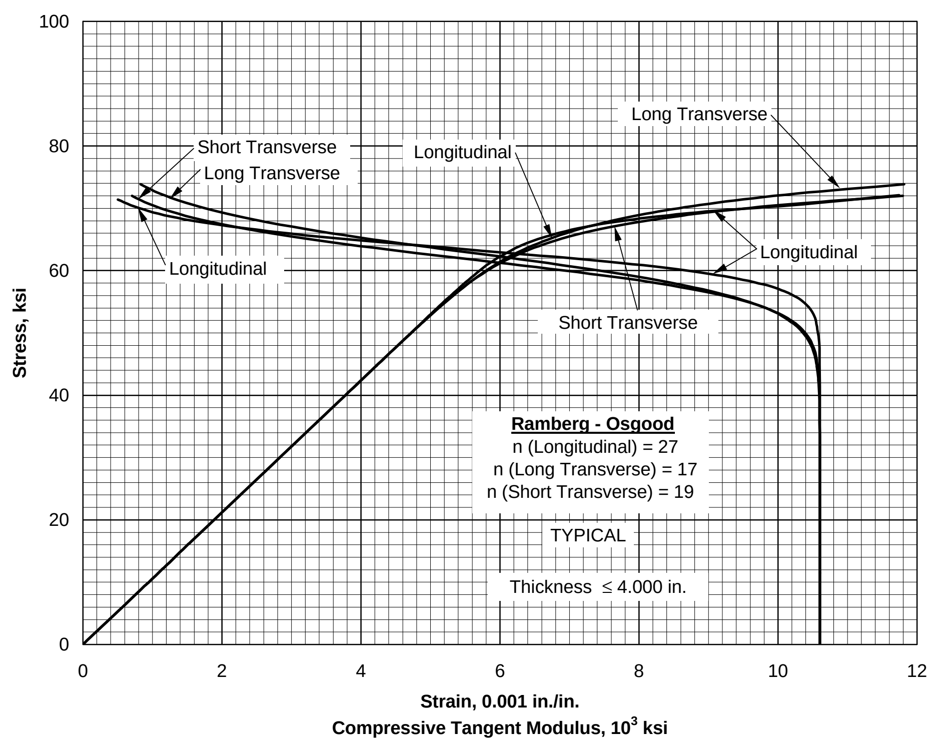

Figure 3.7.8.2.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for 7175-T74 aluminum alloy hand forging at room temperature.

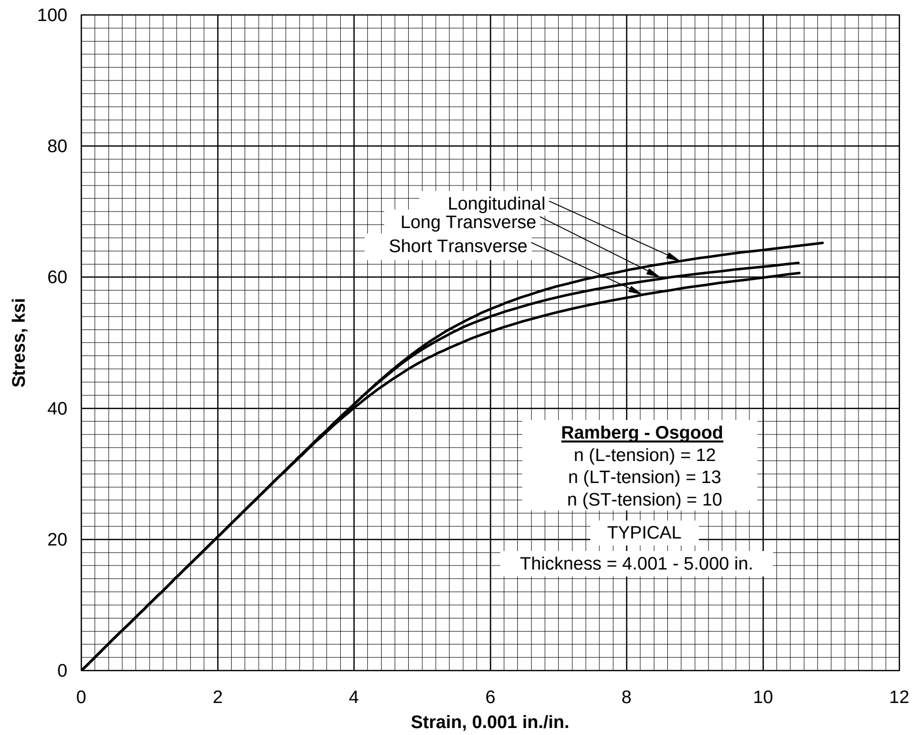

Figure 3.7.8.2.6(e). Typical tensile stress-strain curves for aluminum alloy 7175-T7452 hand forging at room temperature.

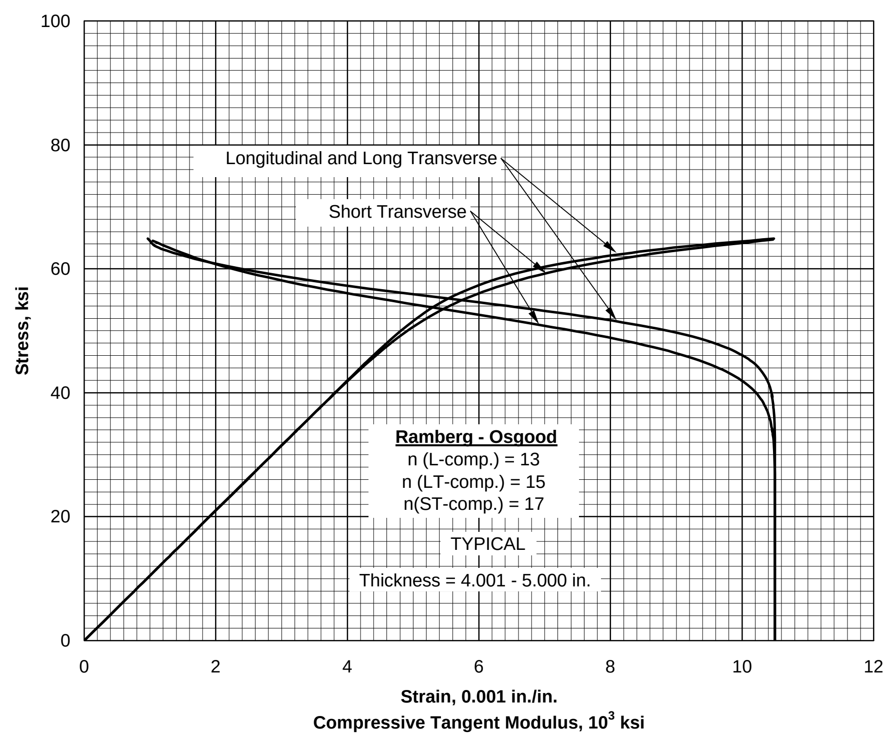

Figure 3.7.8.2.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for aluminum alloy 7175-T7452 hand forging at room temperature.

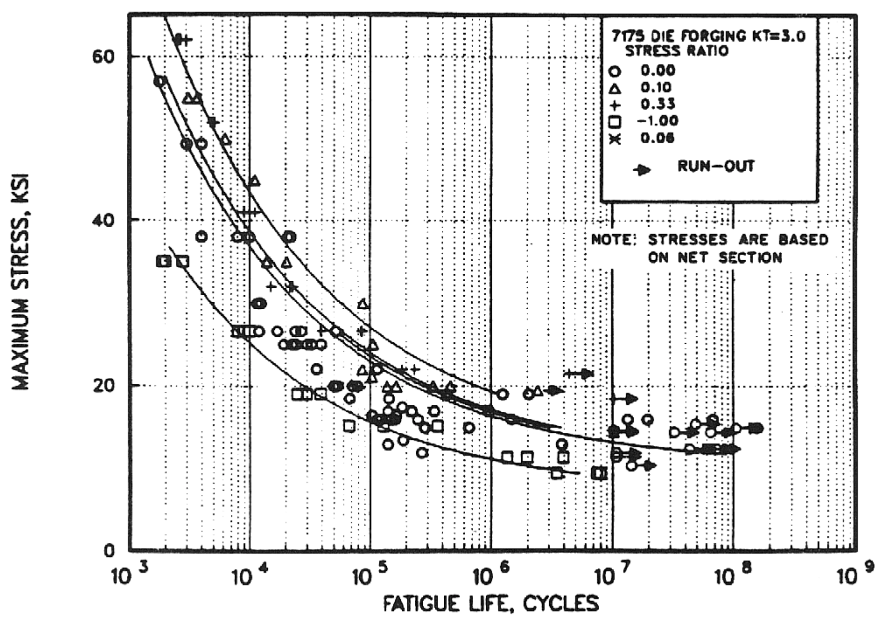

Figure 3.7.8.2.8(a). Best-fit S/N curves for notched, K_t=3.0, 7175-T74 alloy die forging, longitudinal direction.

Correlative Information for Figure 3.7.8.2.8(a)

Product Form: Die forging, 2.0 to 3.0-inch thick, unspecified thickness

Properties: TUS, ksi TYS, ksi

77-82 69-75

Specimen Details: Circumferential notch, K_t = 3
0.3-inch gross diameter
0.25-inch net diameter
Rectangular notched 0.10 x 0.20-inch

Surface Condition: Not specified

References: 3.2.5.1.9(d), 3.7.2.1.8(c), (d), 3.7.8.2.8(a), (b), and (c)

Test Parameters:
Loading - Axial
Frequency - 1200 cpm unspecified
Temperature - 70°F
Environment - Air

No. of Heats/Lots: 13

Equivalent Stress Equation:
Log N_f = 7.88-3.09 log (S_{eq}-7.15)
$S_{eq} = S_a + 0.37S_m$
Std. Error of Estimate, Log (Life) = 7.38 (1/S_{eq})
Standard Deviation, Log (Life) = 1.95
R^2 = 83%

Sample Size = 137

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

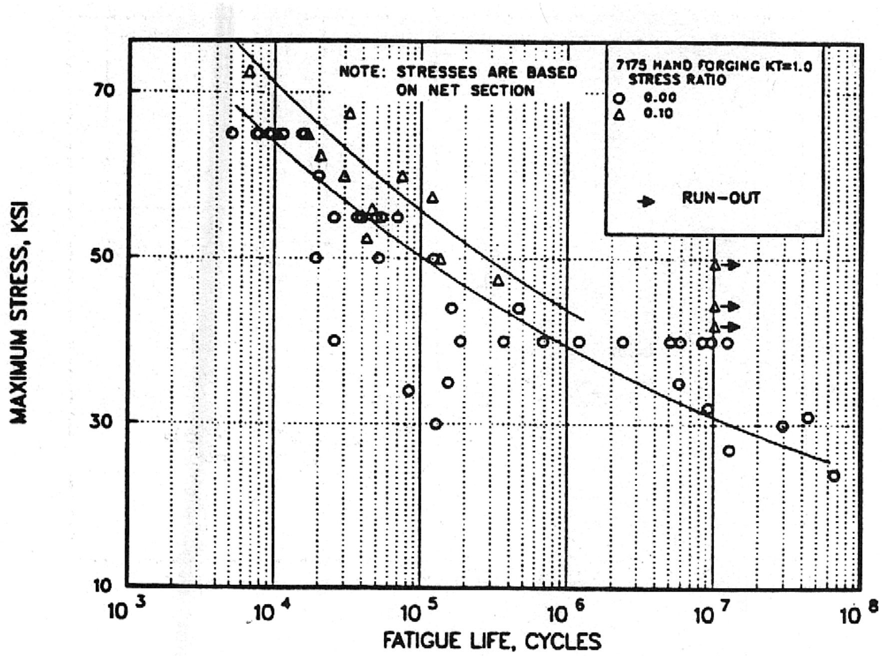

Figure 3.7.8.2.8(b). Best-fit S/N curves for unnotched 7175-T74 alloy hand forging, longitudinal and transverse directions.

Correlative Information for Figure 3.7.8.2.8(b)

Product Form: Hand forging, 2.0 to 6.25-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	71-77	60-68	70

Specimen Details: Uniform gage length
3.0-inch diameter
Hourglass gage section
0.25-inch minimum diameter

References: 3.2.5.1.9(d) 3.7.2.1.8(c) and (d)

Test Parameters:
Loading - Axial
Frequency - 1200 cpm
Temperature - 20°F
Environment - Air

No. of Heats/Lots: Not Specified

Equivalent Stress Equation:
$\text{Log } N_f = 21.15\text{-}9.49 \log (S_{eq})$
$S_{eq} = S_{max} (1\text{-}R)$
Std. Error of Estimate, Log (Life) = $23.33(1/S_{eq})$
Standard Deviation, Log (Life) = 1.55
$R^2 = 76\%$

Sample Size: 50

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

3.7.9 7249 ALLOY

3.7.9.0 ***Comments and Properties*** — 7249 is an Al-Zn-Mg-Cu-Cr alloy developed as a derivative from alloy 7149. Alloy 7249 has tighter compositional tolerances on its major constituents and lowered maximums on the interstitials such as Si, Fe, Mn, and Ti than alloy 7149.

7249-T7452 was developed as a replacement material for 7075-T6 forgings, which are susceptible to stress-corrosion cracking and exfoliation. 7249 also has higher strength at the higher thickness ranges and higher ductility than 7075-T6.

Material specifications for 7249 are shown in Table 3.7.9.0(a). Room temperature mechanical properties are shown in Table 3.7.9.0(b).

Table 3.7.9.0(a). Material Specification for 7249 Alloy

Specification	Form
AMS 4334	Hand forging

The temper index for 7249 is as follows:

Section	Temper
3.7.9.1	T7452

3.7.9.1 ***T7452 Temper*** — Figures 3.7.9.1.6(a) and (b) presents the typical tensile and compressive stress-strain curves and compressive tangent-modulus curves at room temperature. Figure 3.7.9.1.6(c) presents the full range stress-strain curves for hand forged material at room temperature.

Table 3.7.9.0(b). Design Mechanical and Physical Properties of 7249 Aluminum Alloy Hand Forging

Specification	AMS 4334									
Form	Hand forging									
Temper	T7452									
Thickness, in.	≤1.500	1.501-2.000	2.001-2.500	2.501-3.000	3.001-3.500	3.501-3.900	3.901-4.500	4.501-5.000	5.001-5.500	5.501-6.000
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	76	75	74	73	72	71	69	68	67	66
LT	76	75	74	73	72	71	69	68	67	66
ST	...	...	...	...	72	71	69	68	67	66
F_{ty}, ksi:										
L	68	67	66	64	63	61	59	58	56	55
LT	68	67	66	64	63	61	59	58	56	55
ST	...	...	...	...	59	58	57	56	54	53
F_{cy}, ksi:										
L	66	65	64	62	61	59	57	56	54	53
LT	70	69	68	66	65	63	61	60	58	57
ST	73	72	71	68	67	65	63	62	60	59
F_{su}, ksi:										
L[a]	49	48	47	47	46	46	44	44	43	42
LT[a]	47	46	46	45	45	44	43	42	41	41
F_{bru}[b], ksi:										
(e/D = 1.5)	107	106	104	103	101	100	97	96	94	93
(e/D = 2.0)	137	135	134	132	130	128	125	123	121	119
F_{bry}[b], ksi:										
(e/D = 1.5)	94	93	91	88	87	84	82	80	77	76
(e/D = 2.0)	109	107	106	102	101	98	94	93	90	88
e, percent:										
L	12				12					
LT	10				10					
ST	...				5					
E, 10^3 ksi	10.1									
E_c, 10^3 ksi	10.4									
G, 10^3 ksi	3.8									
μ	0.33									
Physical Properties:										
ω, lb/in.^{3}	...									
C, K, and α	...									

a Determined in accordance with ASTM B769.
b Bearing values are “dry pin” values per Section 1.4.7.1.

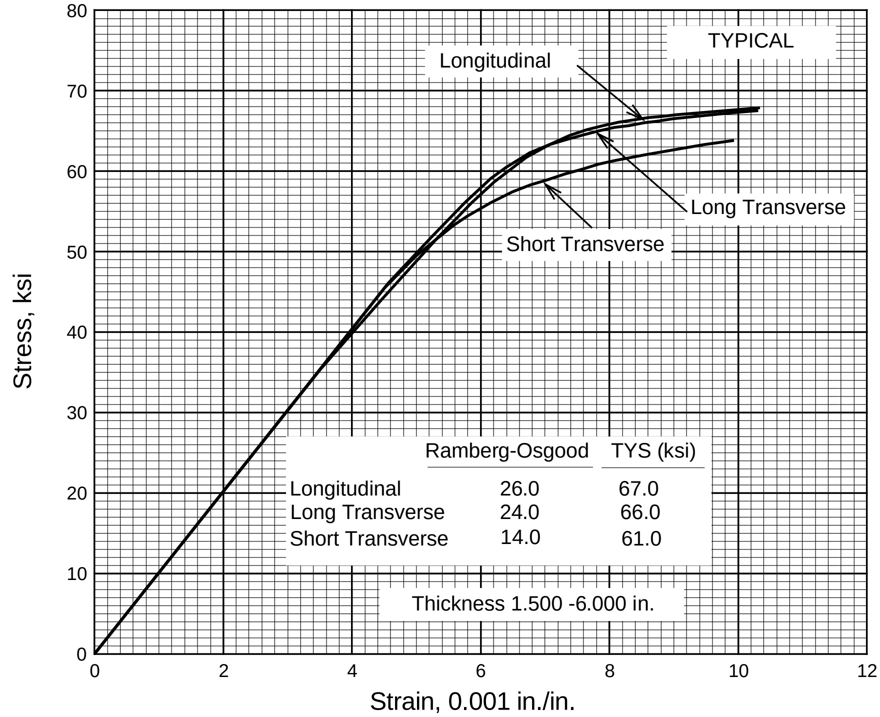

Figure 3.7.9.1.6(a). Typical tensile stress-strain curves for 7249-T7452 aluminum alloy hand forging at room temperature.

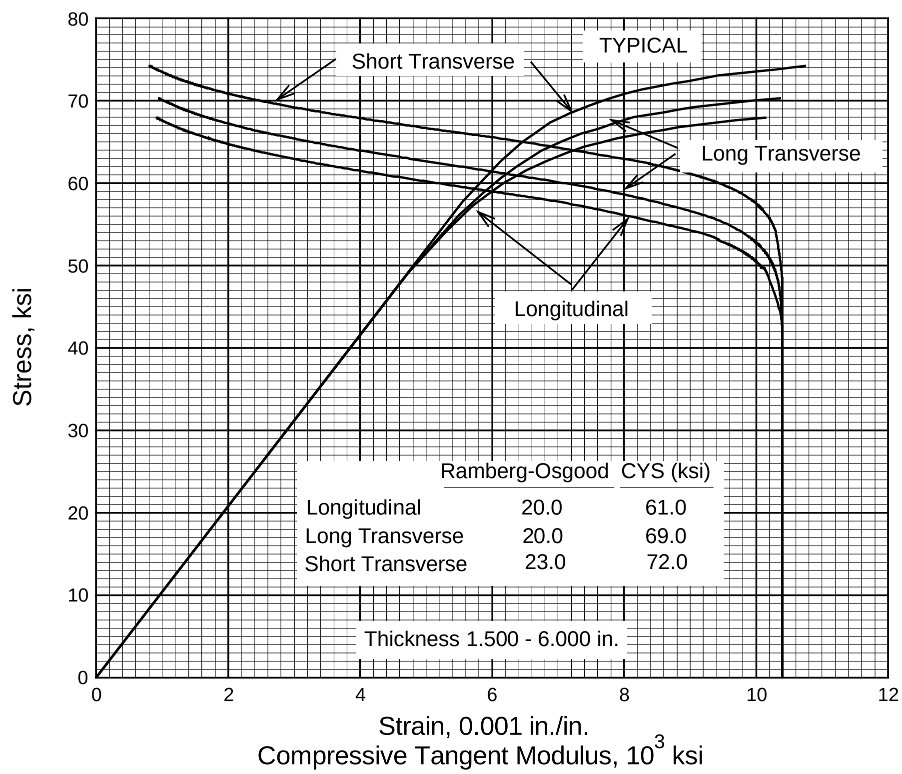

Figure 3.7.9.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7249-T7452 aluminum alloy hand forging at room temperature.

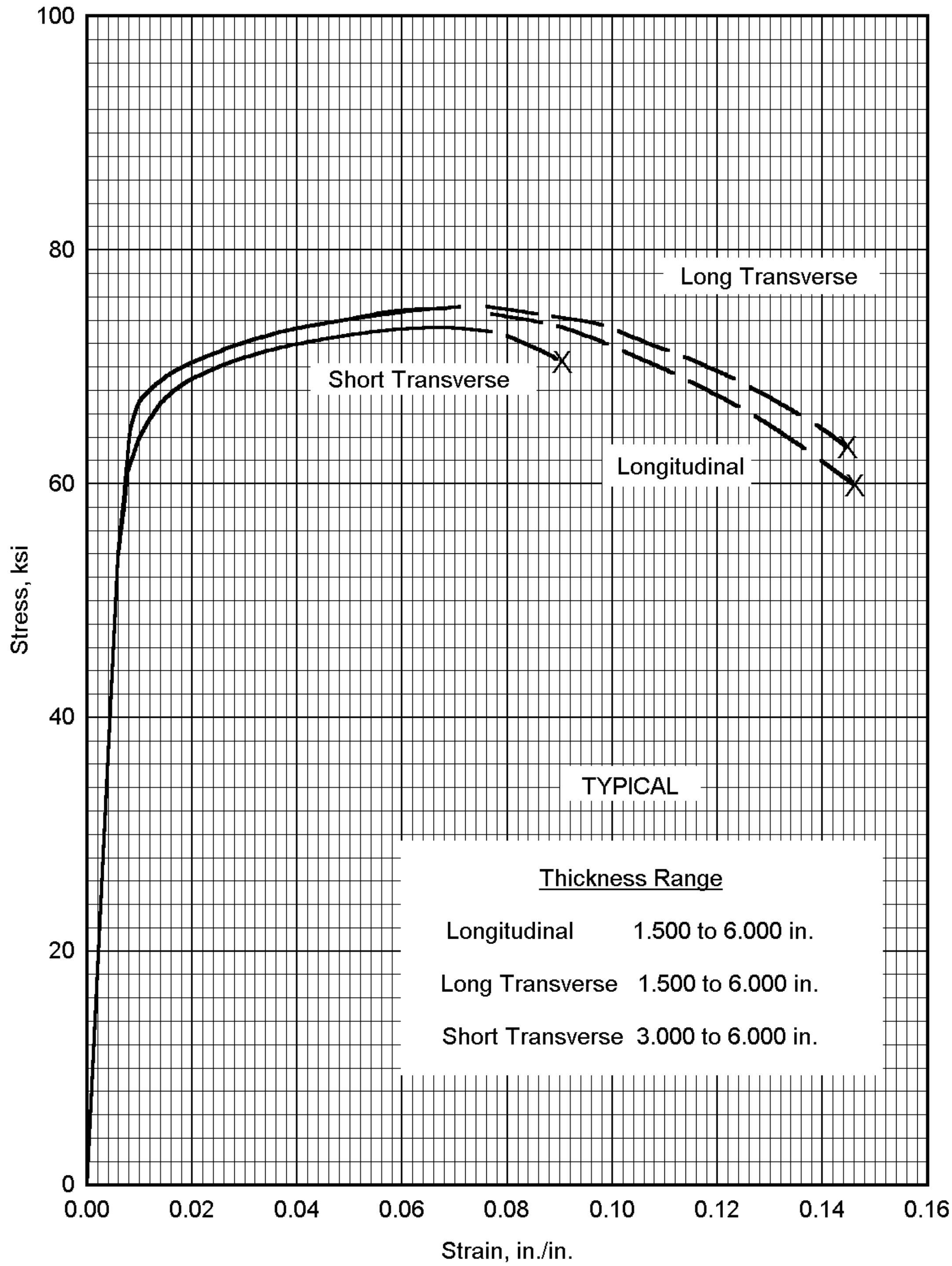

Figure 3.7.9.1.6(c). Typical tensile stress-strain curves (full range) for 7249-T7452 aluminum alloy hand forging at room temperature.

3.7.10 7475 ALLOY

3.7.10.0 ***Comments and Properties*** — 7475 is an Al-Zn-Mg-Cu alloy developed for applications requiring the high strength of 7075 but having fracture toughness superior to that of 7075. Sheet is available in the T61 and T761 tempers and plate in the T651 and T7651 tempers. Sheet has strength approximately the same as that of 7075 combined with toughness about the same as 2024-T3 at room temperature. Plate has strengths similar to those of corresponding tempers of 7075; the toughness of 7475-T651 equals or exceeds that of 7075-T7351.

Resistance to stress-corrosion cracking and exfoliation are comparable to that of 7075. The T73-type temper provides for much improved stress-corrosion resistance over T6-type temper with a decrease in strength. The T76-type temper provides for improved exfoliation resistance and stress-corrosion resistance over T6-type temper with some decrease in strength. Refer to Section 3.1.2.3.1 for information regarding resistance to stress-corrosion cracking.

Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

Material specifications are shown in Table 3.7.10.0(a). Room-temperature mechanical and physical properties are shown in Tables 3.7.10.0(b) through (d).

Table 3.7.10.0(a). Material Specifications for 7475 Aluminum Alloy

Specification	Form
AMS 4084	Bare sheet
AMS 4085	Bare sheet
AMS 4090	Bare plate
AMS 4089	Bare plate
AMS 4202	Bare plate
AMS 4207	Clad sheet
AMS 4100	Clad sheet

The temper index for 7475 is as follows:

Section	Temper
3.7.10.1	T61 and T651
3.7.10.2	T7351
3.7.10.3	T761 and T7651

3.7.10.1 ***T61 and T651 Tempers*** — Figures 3.7.10.1.6(a) through (f) present tensile and compressive stress-strain and tangent-modulus curves for T61 sheet and T651 plate. Figure 3.7.10.1.6(g) contains full-range tensile curves for T61 sheet. Fatigue data for sheet are shown in Figures 3.7.10.1.8(a) through (c). Graphical displays of the residual behavior strength of middle-tension-cracked panels are presented in Figures 3.7.10.1.10(a) through (d).

3.7.10.2 ***T7351 Temper*** — Figures 3.7.10.2.6(a) and (b) present tensile and compressive stress-strain and tangent-modulus curves for T7351 plate. Fatigue data for 7475-T7351 plate are presented in Figures 3.7.10.2.8(a) and (b). Figures 3.7.10.2.9(a) and (b) present fatigue-crack-propagation data for T7351 plate.

3.7.10.3 ***T761 and T7651 Tempers*** — Figures 3.7.10.3.6(a) through (j) present tensile and compressive stress-strain and tangent-modulus curves for T761 bare and clad sheet and T7651 plate. Figures 3.7.10.3.6(k) and (1) contain full-range tensile stress-strain curves for T761 bare and clad sheet, respectively. Fatigue data for 7475-T761 sheet are presented in Figures 3.7.10.1.8(a) through (c). Fatigue data for 7475-T7651 plate are shown in Figure 3.7.10.2.8(b). Graphical displays of the residual strength behavior of middle-tension-cracked tension panels are presented in Figures 3.7.10.3.10(a) and (b).

Table 3.7.10.0(b). Design Mechanical and Physical Properties of 7475 Aluminum Alloy Sheet and Plate

Specification	AMS 4084	AMS 4090			AMS 4085			AMS 4089		
Form	Sheet	Plate			Sheet			Plate		
Temper	T61	T651			T761			T7651		
Thickness, in.	0.040-0.249	0.250-0.499	0.500-1.000	1.001-1.500	0.040-0.062	0.063-0.187	0.188-0.249	0.250-0.499	0.500-1.000	1.001-1.500
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	75	77	77	77	71	71	71	70	69	69
LT	75	78	78	78	71	71	71	71	70	70
F_{ty}, ksi:										
L	66	69	70	70	61	61	61	60	59	59
LT	64	67	68	68	60	60	60	60	59	59
F_{cy}, ksi:										
L	64	67	68	67	60	59	58	60	59	59
LT	68	70	71	71	61	63	63	63	62	59
F_{su}, ksi	45	44	43	41	43	42	41	41	39	37
F_{bru}[a], ksi:										
(e/D = 1.5)	120	113	113	113	112	112	111	104	103	103
(e/D = 2.0)	154	144	144	144	143	143	142	136	134	134
F_{bry}[a], ksi:										
(e/D = 1.5)	97	91	93	93	90	90	90	82	81	81
(e/D = 2.0)	110	106	107	107	104	104	104	97	95	95
e, percent:										
L	9	10	9	9	9	9	9	9	8	6
LT	9	10	9	9	9	9	9	9	8	6
E, 10^3 ksi	10.0	10.2			10.0			10.2		
E_c, 10^3 ksi	10.5	10.6			10.5			10.6		
G, 10^3 ksi	3.8	3.9			3.8			3.9		
μ	0.33	0.33			0.33			0.33		
Physical Properties:										
ω, lb/in.^{3}	0.101									
C, K, and α	0.23 (at 212°F)									
K, Btu/[(hr)(ft^2)(°F)/ft]	80 (at 77°F) for T61 and T651; 90 (at 77°F) for T761 and T7651									
α, 10^{-6} in./in./°F	12.9 (68 to 212°F)									

a See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.10.0(c). Design Mechanical and Physical Properties of 7475 Aluminum Alloy Plate

Specification	AMS 4202											
Form	Plate											
Temper	T7351											
Thickness, in.	0.250-1.500		1.501-2.000		2.001-2.500		2.501-3.000		3.001-3.500		3.501-4.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi:												
L	70	72	70	71	68	70	68	69	64	67	64	66
LT	71	73	70	72	68	70	68	69	64	68	64	67
ST	66[a]	70[a]	65	69	65	69	65	68	63	67	63	66
F_{ty}, ksi:												
L	59	62	58	60	56	59	56	58	52	56	52	54
LT	60	62	58[b]	61	56	59	56	58	52	56	52	54
ST	54[a]	57[a]	53	56	53	56	53	55	50	53	50	52
F_{cy}, ksi:												
L	58	60	56	59	54	57	53	55	49	53	49	51
LT	61	63	60	63	58	61	58	60	54	58	54	56
ST	62[a]	64[a]	60	63	58	61	58	60	54	58	54	56
F_{su}, ksi	41	42	42	43	41	42	41	42	39	42	39	41
F_{bru}[c], ksi:												
(e/D = 1.5)	102	105	103	106	101	104	101	103	97	102	97	101
(e/D = 2.0)	132	136	134	138	131	135	131	134	125	133	125	131
F_{bry}[c], ksi:												
(e/D = 1.5)	81	84	82	86	81	84	81	84	77	82	77	80
(e/D = 2.0)	97	101	97	102	95	100	95	99	89	96	89	93
e, percent (S-basis):												
L	10	...	10	...	10	...	10	...	10	...	9	...
LT	9	...	8	...	8	...	8	...	8	...	7	...
ST	4[b]	...	4	...	4	...	3	...	3	...	3	...
E, 10^3 ksi	10.3											
E_c, 10^3 ksi	10.6											
G, 10^3 ksi	3.9											
μ	0.33											
Physical Properties:												
ω, lb/in.^{3}	0.101											
C, Btu/(lb)(°F)	0.21 (at 212°F)											
K, Btu/[(hr)(ft^2)(°F)/ft]	94 (at 77°F)											
α, 10^{-6} in./in./°F	13.0 (68 to 212°F)											

a Values applicable to 1.500-inch thickness only.
b S-basis. The rounded T_{99} value for F_{ty}(LT) = 59 ksi.
c See Table 3.1.2.1.1. Bearing values are "dry pin" values per Section 1.4.7.1.

Table 3.7.10.0(d). Design Mechanical and Physical Properties of Clad 7475 Aluminum Alloy Sheet

Specification	AMS 4207				AMS 4100				
Form	Sheet								
Temper	T61				T761				
Thickness, in.	0.040-0.062	0.063-0.187		0.188-0.249	0.040-0.062	0.063-0.187		0.188-0.249	
Basis	S	A	B	S	S	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	69	69	73	72	66	67	70	68	71
LT	69	70	73	72	66	68	70	70	72
F_{ty}, ksi:									
L	61	64	67	63	56	58	61	59	63
LT	59	60[a]	64	61	55	57	60	60	62
F_{cy}, ksi:									
L	60	61	65	62	55	56	59	58	60
LT	63	64	68	65	58	59	62	61	63
F_{su}, ksi	42	40	41	39	41	40	41	40	41
F_{bru}[b], ksi:									
(e/D = 1.5)	110	111	116	115	104	107	110	108	111
(e/D = 2.0)	140	142	148	146	133	136	140	138	142
F_{bry}[b], ksi:									
(e/D = 1.5)	89	90	96	92	83	86	90	90	93
(e/D = 2.0)	102	104	111	106	97	101	106	106	110
e, percent (S-basis):									
LT	9	9	...	9	9	9	...	9	...
E, 10^3 ksi:									
Primary	10.0	10.0		10.0	10.0	10.0		10.0	
Secondary	9.2	9.4		9.7	9.2	9.4		9.7	
E_c, 10^3 ksi:									
Primary	10.5	10.5		10.5	10.5	10.5		10.5	
Secondary	9.4	9.7		10.0	9.4	9.7		10.0	
G, 10^3 ksi	3.8	3.8		3.8	3.8	3.8		3.8	
μ	0.33	0.33		0.33	0.33	0.33		0.33	
Physical Properties:									
ω, lb/in.^{3}	0.101								
C, K, α	...								

a S-basis. The rounded T_{99} value is 61 ksi.

b Bearing values are “dry pin” values per Section 1.4.7.1.

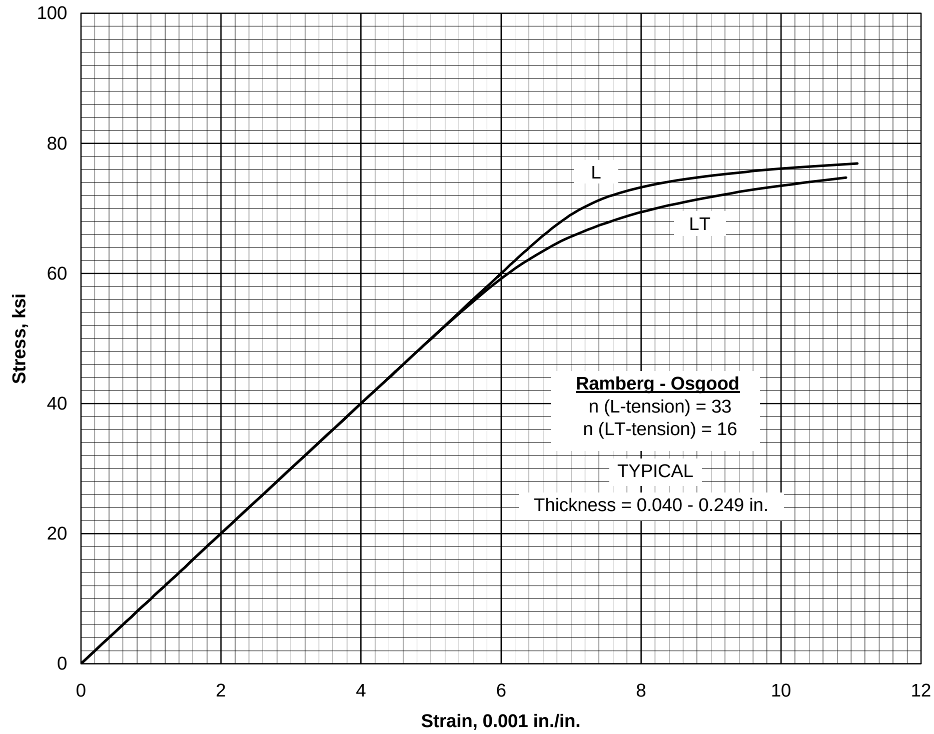

Figure 3.7.10.1.6(a). Typical tensile stress-strain curves for 7475-T61 aluminum alloy sheet at room temperature.

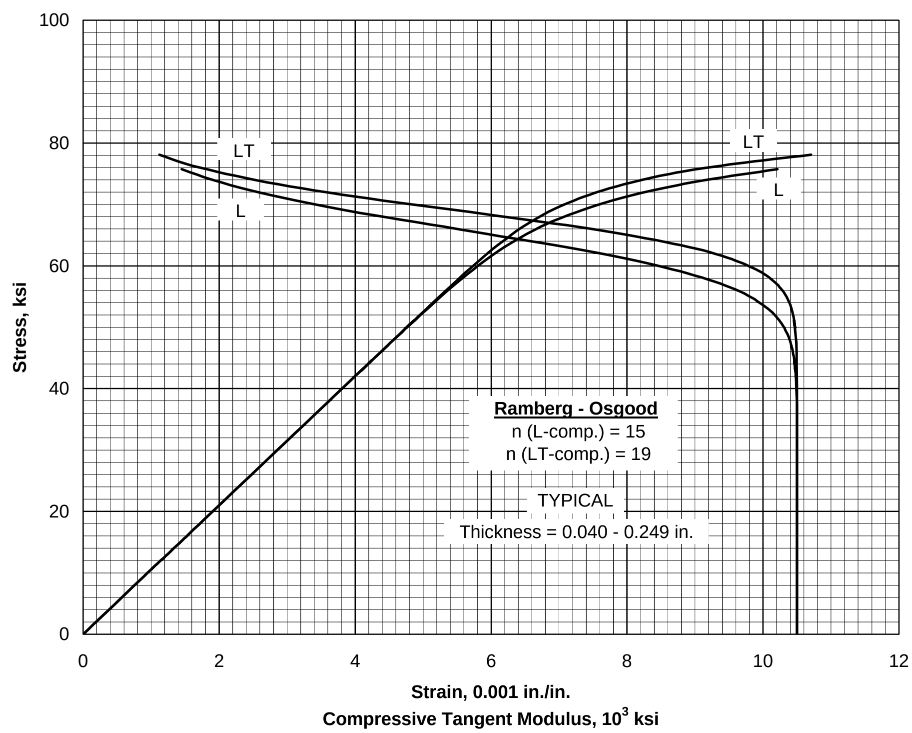

Figure 3.7.10.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T61 aluminum alloy sheet at room temperature.

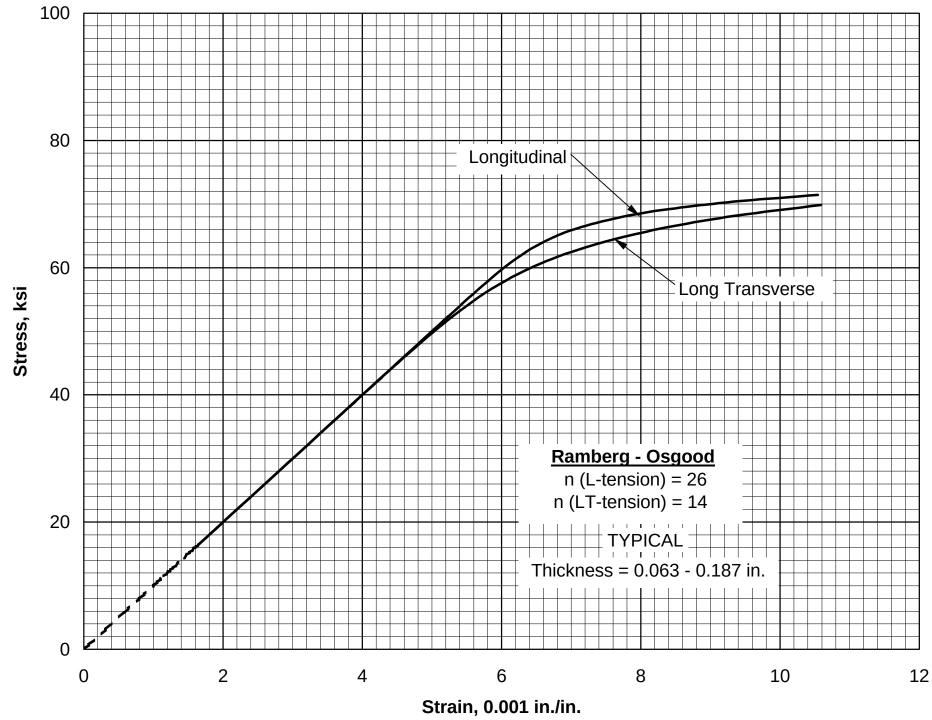

Figure 3.7.10.1.6(c). Typical tensile stress-strain curves for clad 7475-T61 aluminum alloy sheet at room temperature.

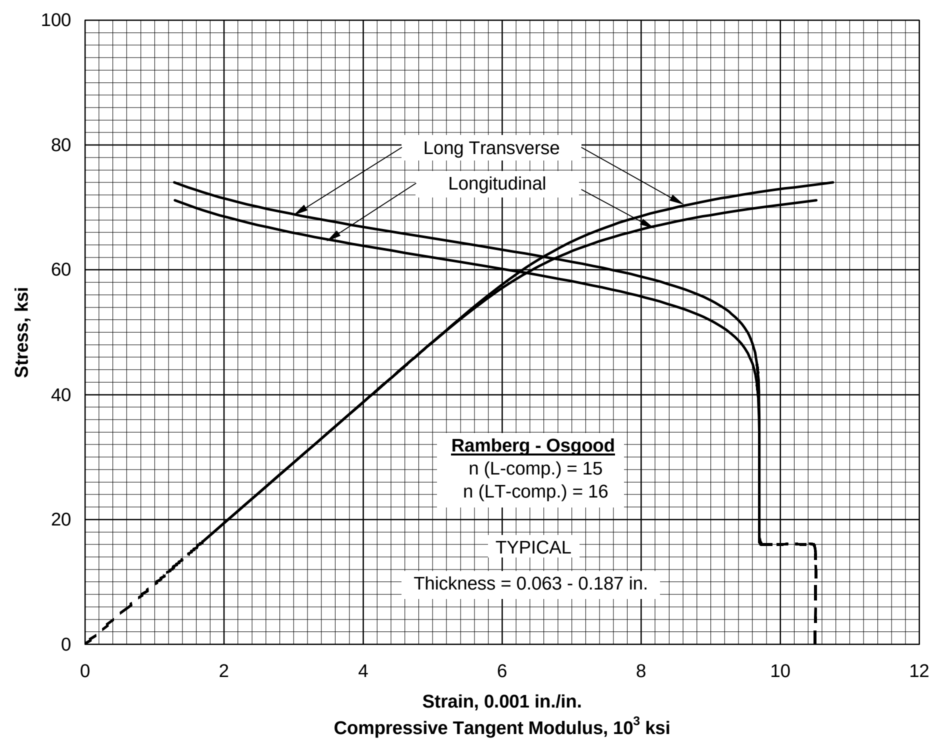

Figure 3.7.10.1.6(d). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T61 aluminum alloy sheet at room temperature.

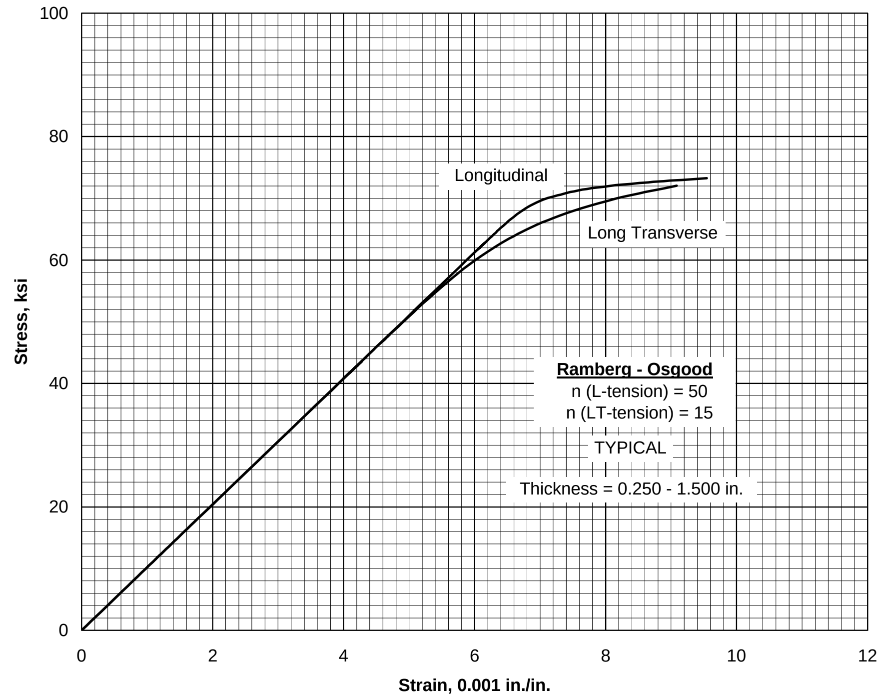

Figure 3.7.10.1.6(e). Typical tensile stress-strain curves for 7475-T651 aluminum alloy plate at room temperature.

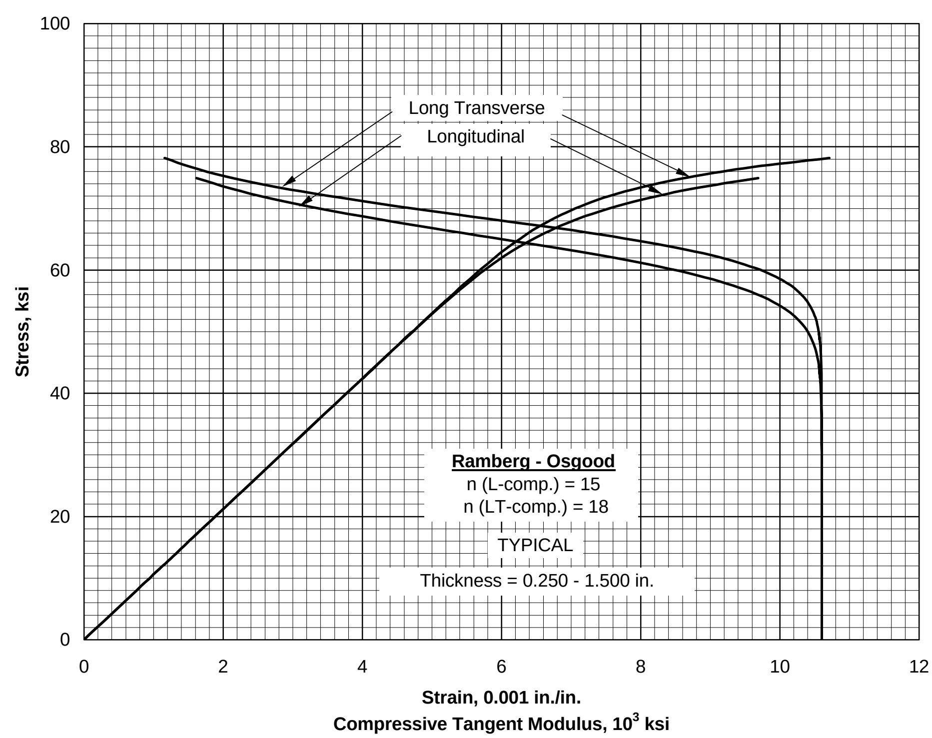

Figure 3.7.10.1.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T651 aluminum alloy plate at room temperature.

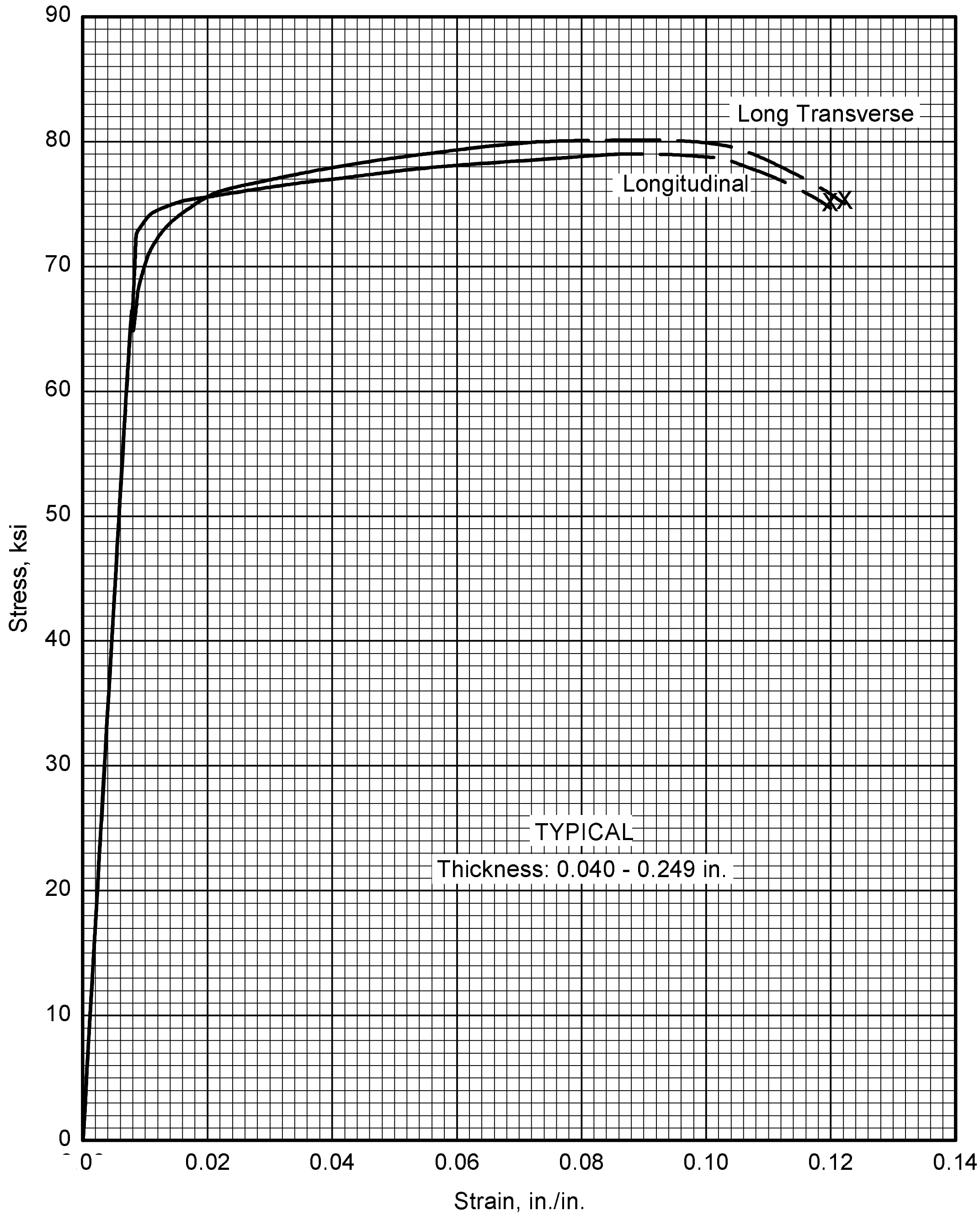

Figure 3.7.10.1.6(g). Typical tensile stress-strain curves (full range) for 7475-T61 aluminum alloy sheet at room temperature.

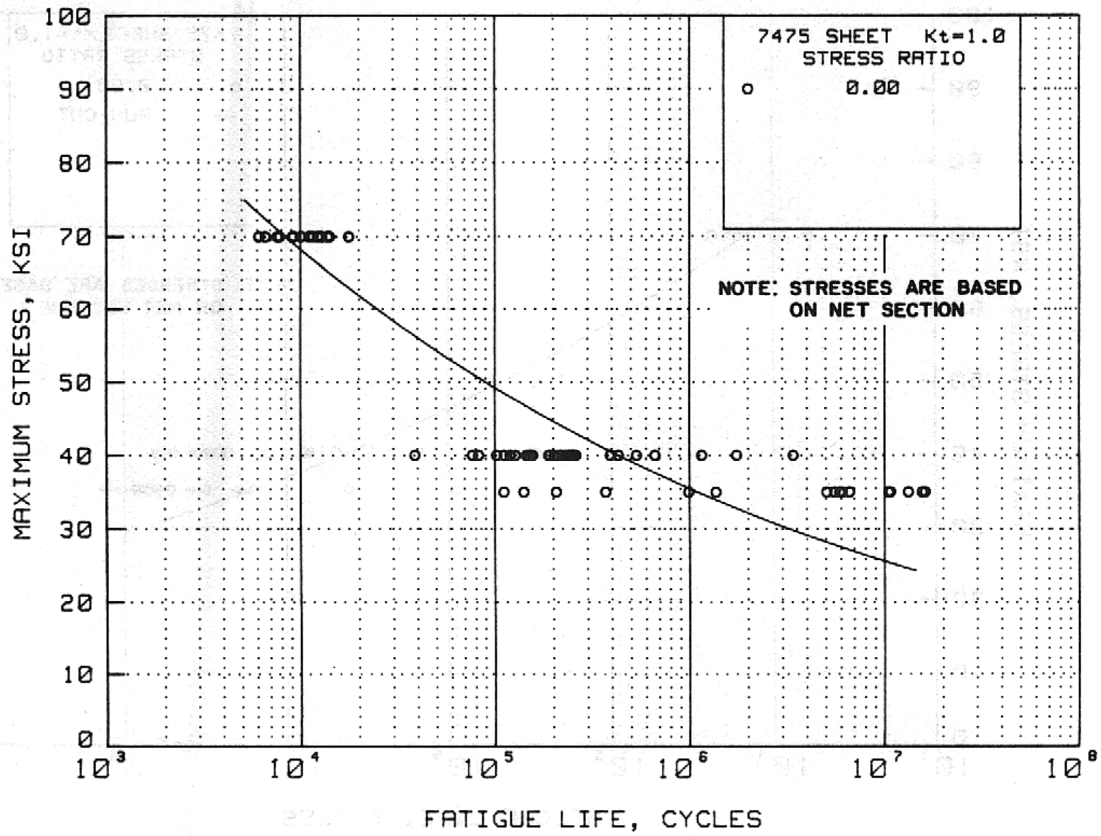

Figure 3.7.10.1.8(a). Best-fit S/N curve for unnotched 7475-T61 and T761 sheet, thickness ≤0.125 inch, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.10.1.8(a)

Product Form: Sheet, 0.032 to 0.125-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
T61 81	73-75	RT	
T761	77	68-70	RT

Specimen Details: Unnotched, hourglass,
0.500-inch diameter
4.00-inch test section radius, r

Surface Condition: As machined

Reference: 3.2.6.1.9(d)

Test Parameters:
Loading - Axial
Frequency - 798, 1500, or 1728 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Maximum Stress Equation:
Log N_f = 16.9-7.03 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.545
Standard Deviation, Log (Life) = 0.988
R^2=70%

Sample Size = 67

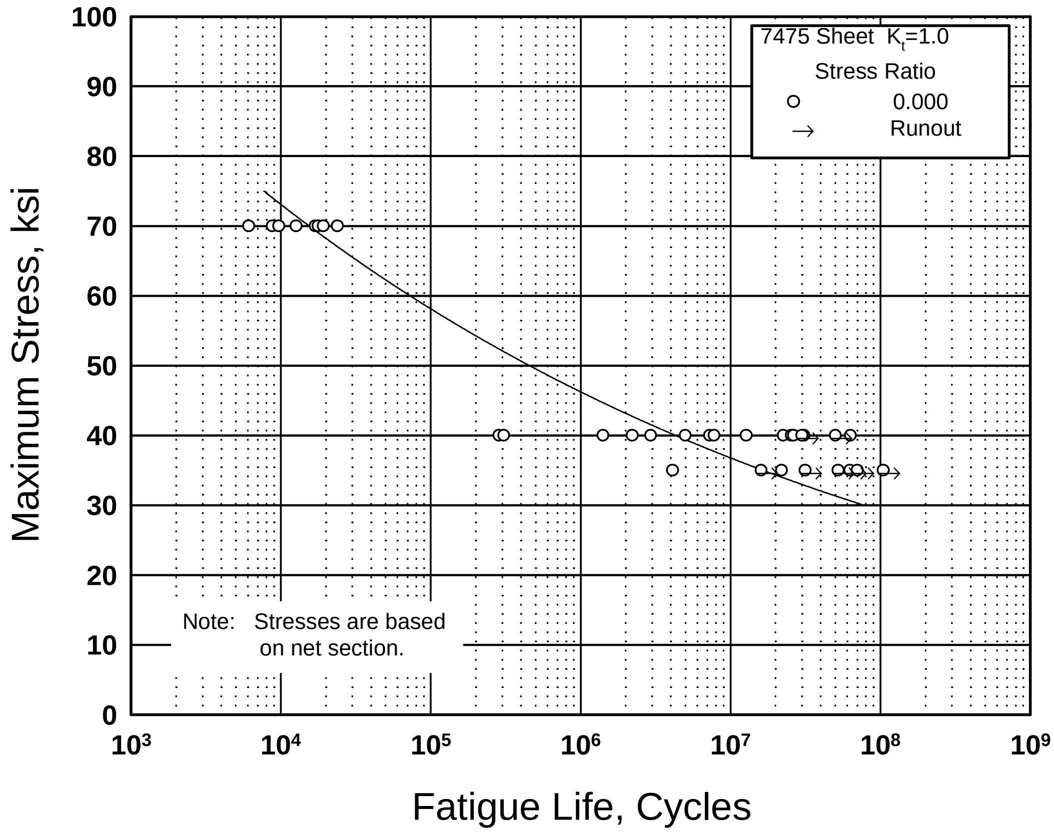

Figure 3.7.10.1.8(b). Best-fit S/N Curve for unnotched 7475-T61 and T761 sheet thickness > 0.125 inch, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.10.1.8(b)

Product Form: Sheet, > 0.125-inch through 0.249 inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
T61	80-81	73-76	RT
T761	75	66-67	RT

Specimen Details: Unnotched, hourglass,
0.500-inch diameter
4.00-inch test section
radius, R

Surface Condition: As machined

Reference: 3.2.6.1.9(d)

Test Parameters:
Loading - Axial
Frequency - 798, 1500, or 1728 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Maximum Stress Equation:
Log N_f = 22.7-10.1 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.657
Standard Deviation, Log (Life) = 1.380
R^2=77%

Sample Size = 24

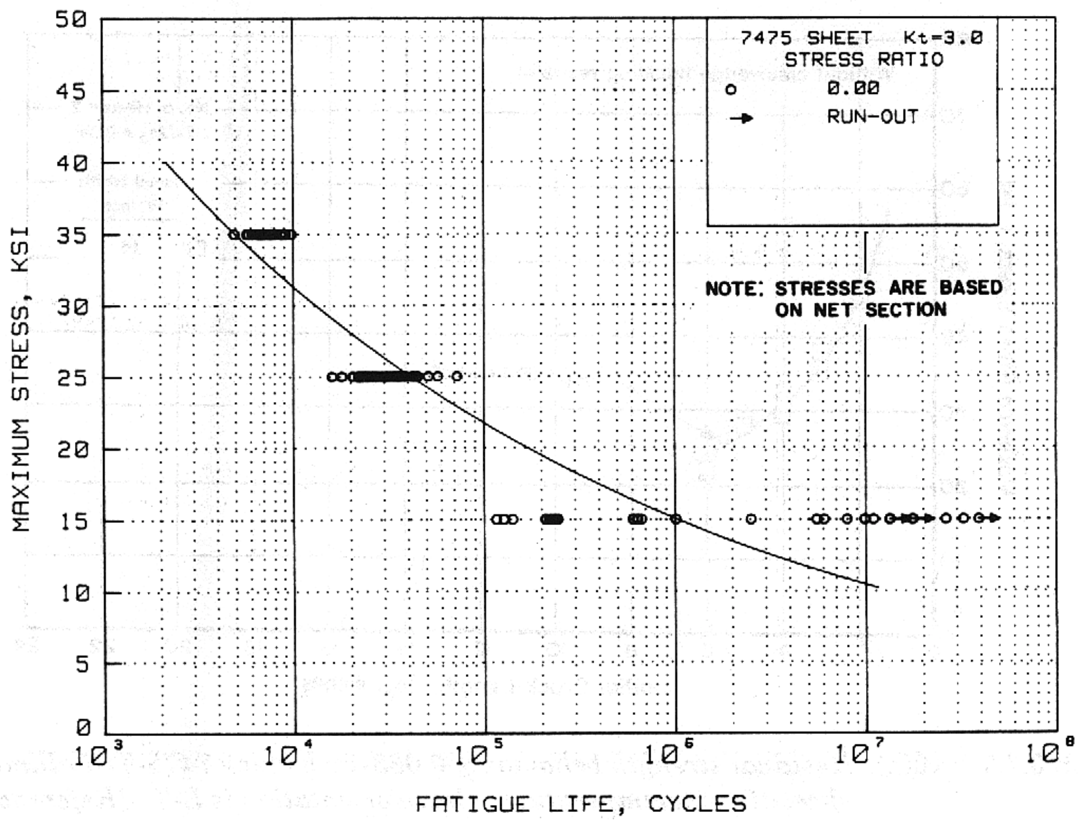

Figure 3.7.10.1.8(c). Best-fit S/N curve for notched, K_t = 3.0, 7475-T61 and T761 sheet, longitudinal and long transverse directions.

Correlative Information for Figure 3.7.10.1.8(c)

Product Form: Sheet, 0.032 to 0.249-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
T61	81-82	73-76	RT
T761	75-77	67-70	RT

Specimen Details: Notched, edge notched
K_t = 3.0

1.000-inch gross width
0.700-inch net width
0.050-inch root radius, r
60° flank angle, ω

Surface Condition: As machined

Reference: 3.2.6.1.9(d)

Test Parameters:
Loading - Axial
Frequency - 798, 1500, or 1728 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 2

Maximum Stress Equation:
Log N_f = 13.4-6.29 log (S_{max})
Std. Error of Estimate, Log (Life) = 0.441
Standard Deviation, Log (Life) = 0.931
R^2=78%

Sample Size = 99

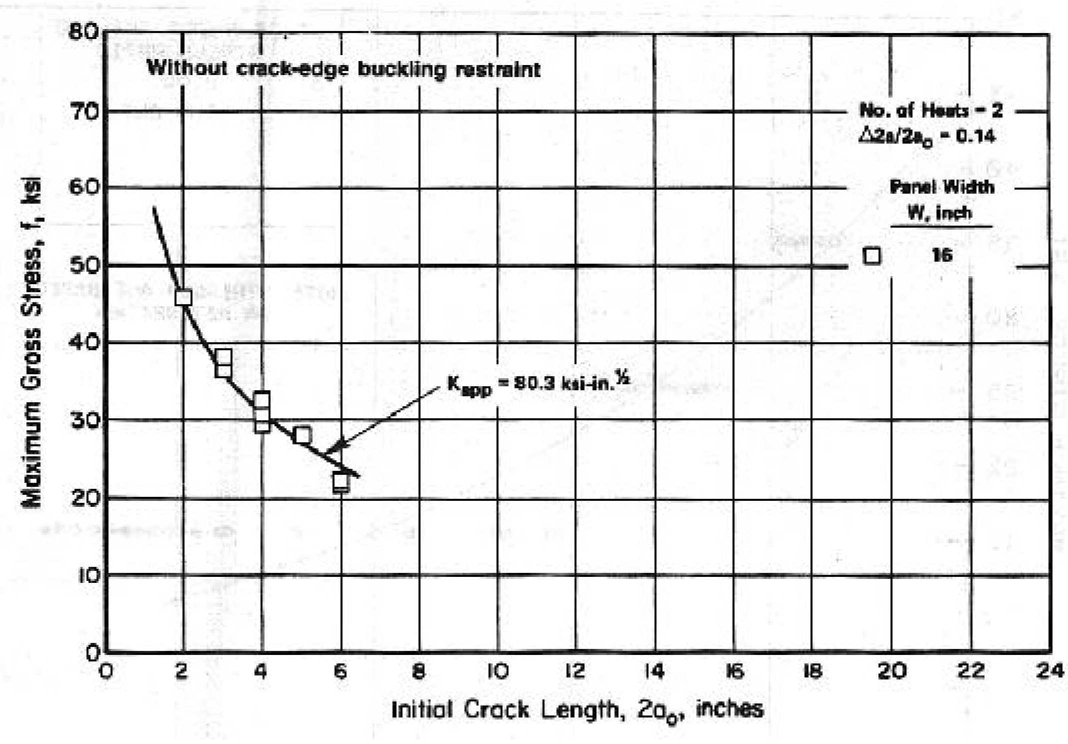

Figure 3.7.10.1.10(a). Residual strength behavior of 0.063-inch-thick 7475-T61 aluminum alloy sheet at room temperature. Crack orientation is L-T. [References 3.1.2.1.6(d) and 3.2.5.1.9(d).]

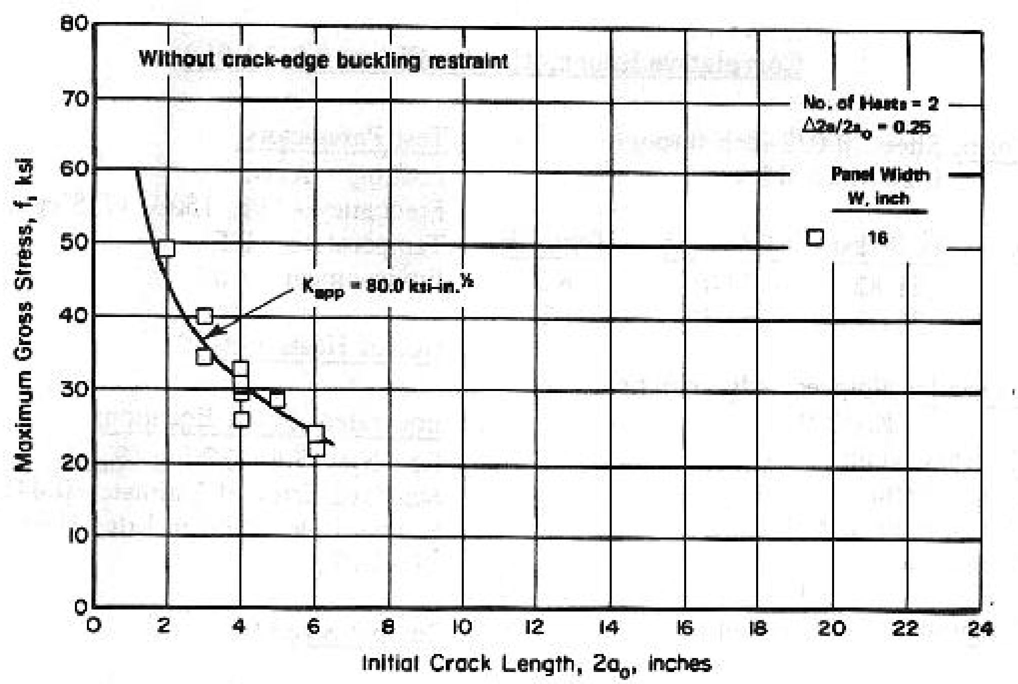

Figure 3.7.10.1.10(b). Residual strength behavior of 0.063-inch-thick 7475-T61 aluminum alloy sheet at room temperature. Crack orientation is T-L. [References 3.1.2.1.6(d) and 3.2.5.1.9(d).]

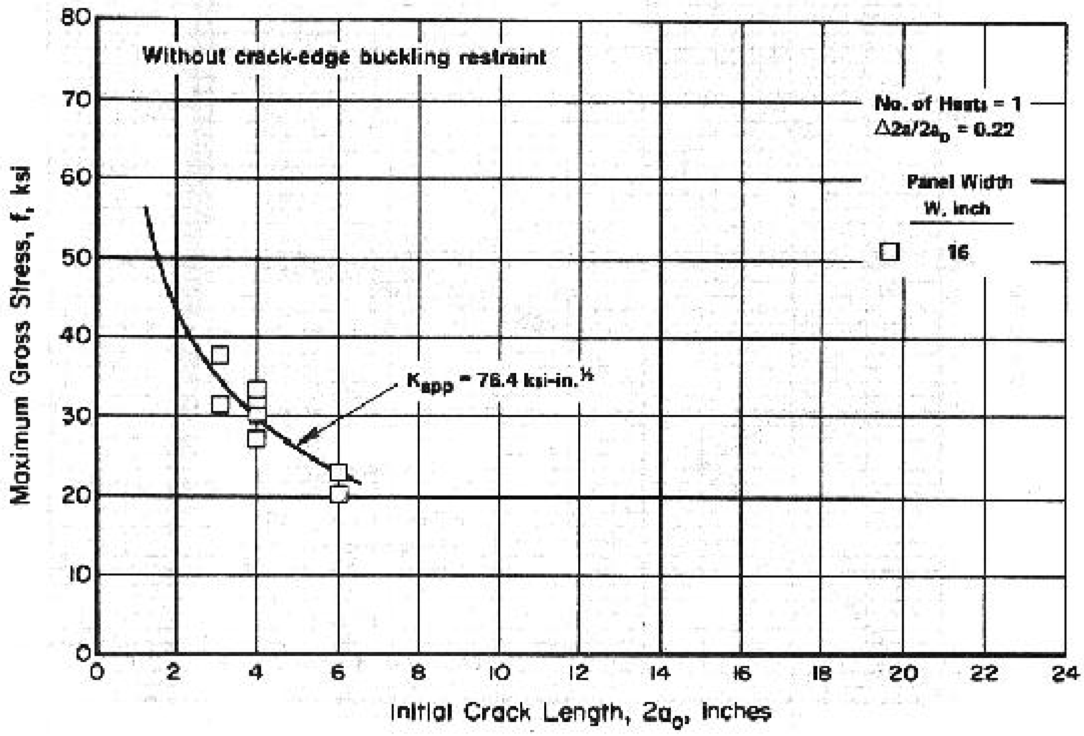

Figure 3.7.10.1.10(c). Residual strength behavior of 0.063-inch-thick 7475-T61 clad aluminum alloy sheet at room temperature. Crack orientation is L-T. [Reference 3.2.5.1.9(d).]

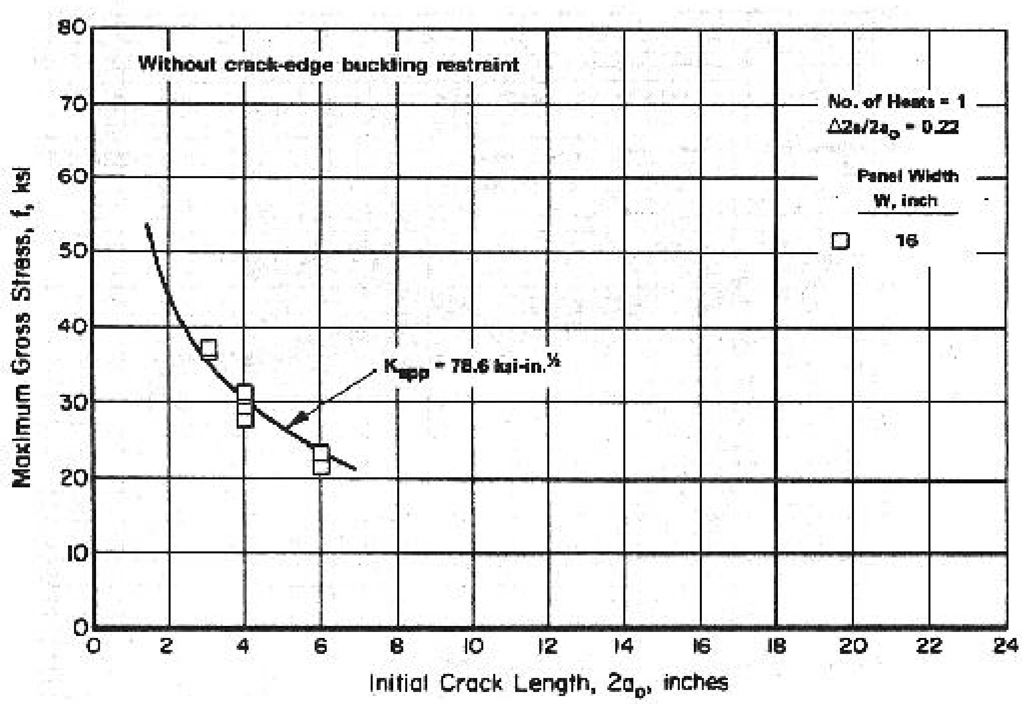

Figure 3.7.10.1.10(d). Residual strength behavior of 0.063-inch-thick 7475-T61 clad aluminum alloy sheet at room temperature. Crack orientation is T-L. [Reference 3.2.5.1.9(d).]

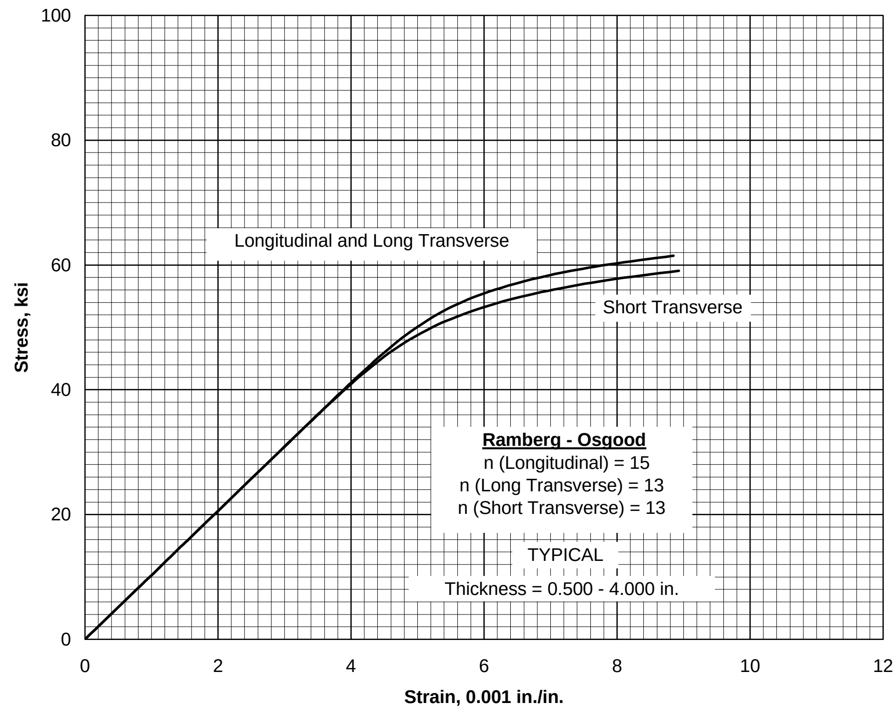

Figure 3.7.10.2.6(a). Typical tensile stress-strain curves for 7475-T7351 aluminum alloy plate at room temperature.

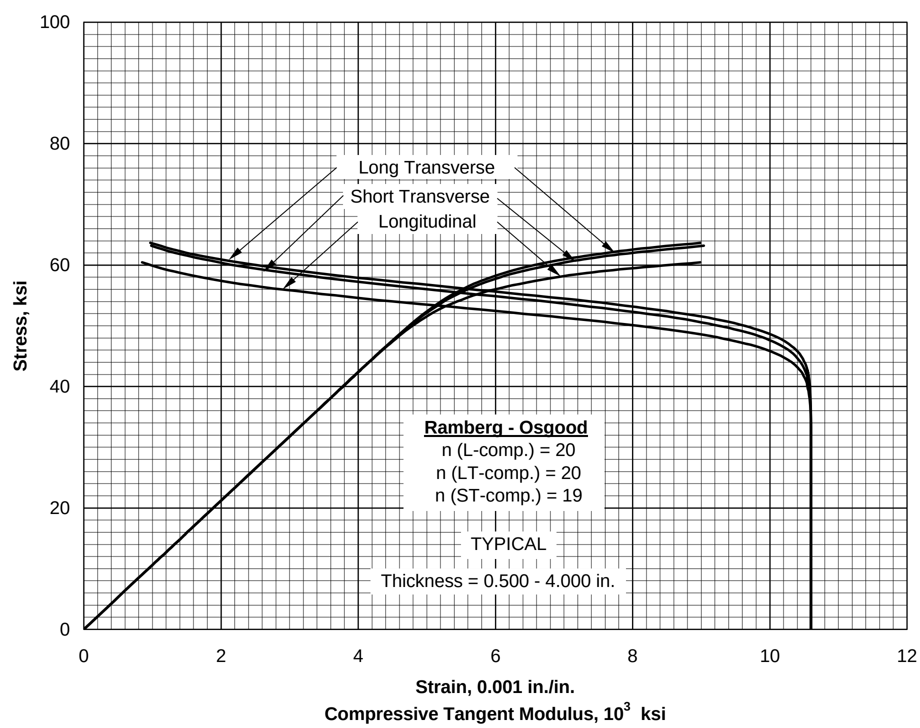

Figure 3.7.10.2.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T7351 aluminum alloy plate at room temperature.

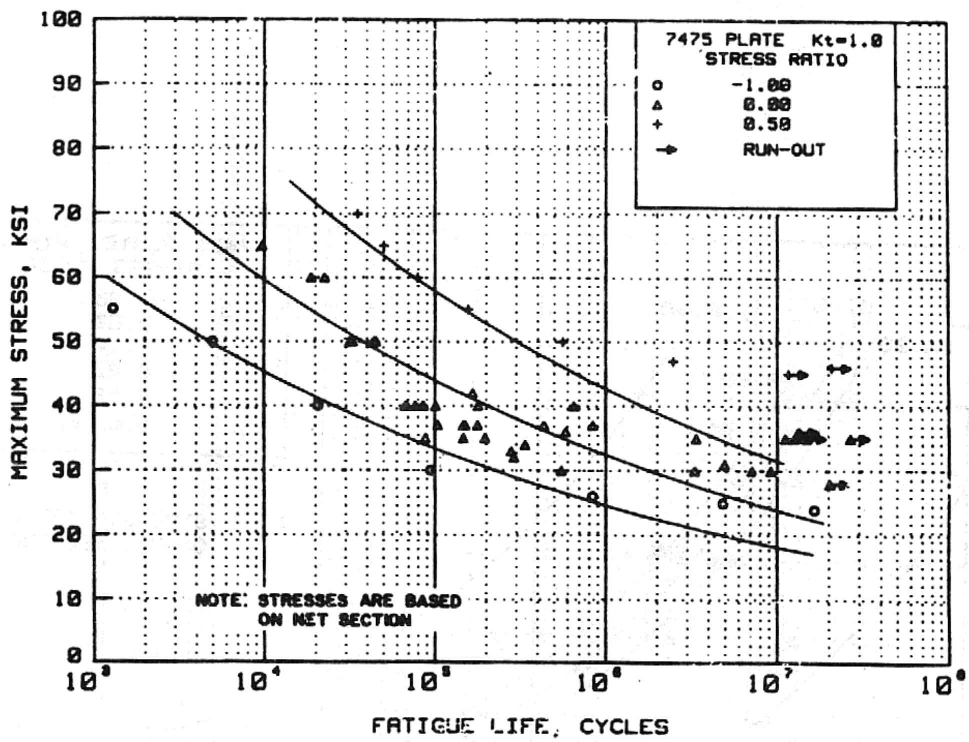

Figure 3.7.10.2.8(a). Best-fit S/N curves for unnotched 7475-T7351 plate, longitudinal and long transverse orientation.

Correlative Information for Figure 3.7.10.2.8(a)

Product Form: Plate, 0.5, 1.0, 2.0, 3.0, and 4.0-inches thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
L	70	60	RT
LT	71	60	RT

Specimen Details: Unnotched
Hourglass, 0.300-inch net diameter
9.875-inch test section radius

Surface Condition: As machined

References: 3.7.10.2.8(a) and (b)

Test Parameters:
Loading — Axial
Frequency — Not specified
Temperature — RT
Environment — Air

No. of Heats/Lots: 5

Equivalent Stress Equation:
Log N_f = 17.42-7.56 log (S_{eq})
$S_{eq} = S_{max}(1-R)^{0.40}$
Std. Error of Estimate, Log (Life) = 0.433
Standard Deviation, Log (Life) = 0.857
R^2 = 74%

Sample Size = 52

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

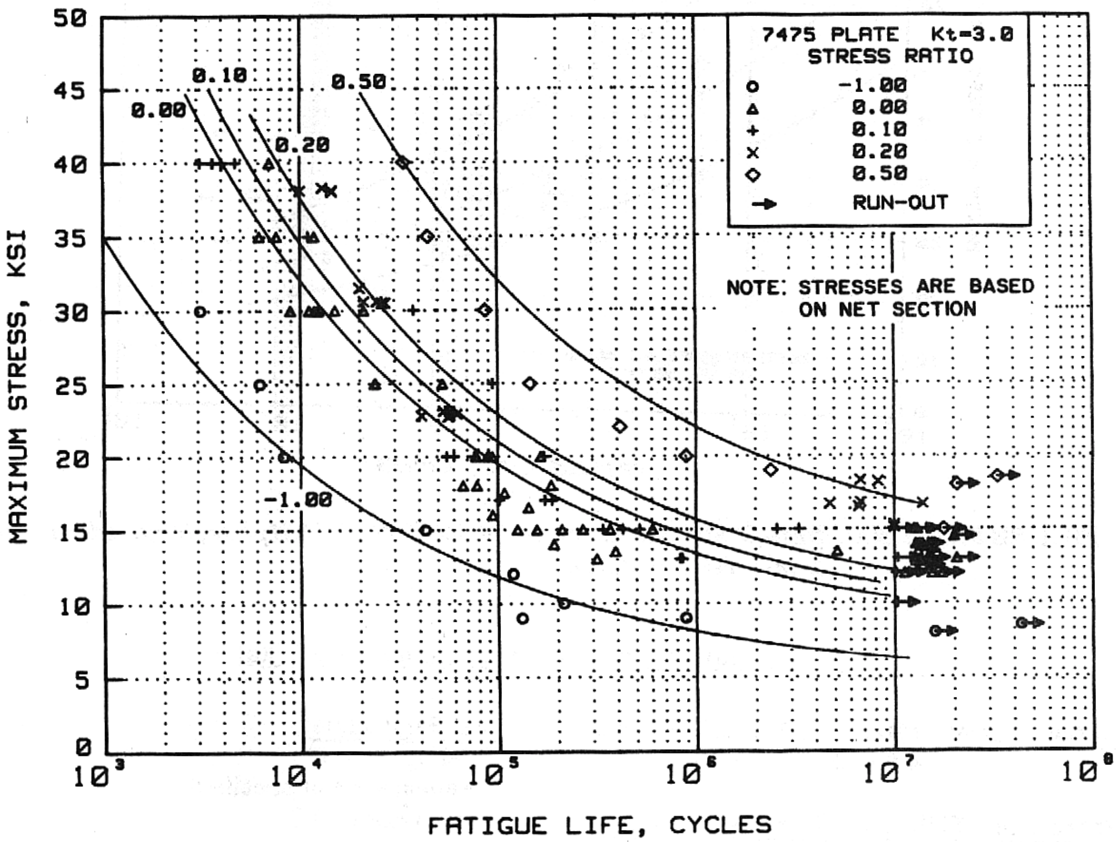

Figure 3.7.10.2.8(b). Best-fit S/N curves for notched, K_t = 3.0, 7475-T7351 and T7651 plate, longitudinal and long transverse direction.

(See following page for correlative information.)

Correlative Information for Figure 3.7.10.2.8(b)

Product Form: Plate, 0.5, 1.0, 1.5, 2.0, 3.0, and 4.0 inches thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
L (T7351)	70	60	RT [Ref. (a)]
LT (T7351)	71	61	RT [Ref (b)]
L (T7351)	72	62	RT [Ref. (c)]
(T7651)	Not specified		[Ref.(d)]
L (T7351)	72	63	RT [Ref. (e)]
LT (T7351)	73	62	RT [Ref. (e)]

Specimen Details: Notched, $K_t = 3.0$

Circumferentially notched [Ref. (a) and (b)]
0.253-inch gross width
0.147-inch net width
0.013-inch root radius, r
60° flank angle, ω

Edge notched [Ref. (c)]
1.00-inch gross width
0.70-inch net width
root radius not specified
60° flank angle, ω

Edge notched [Ref. (d)]
2.25-inch gross width
1.50-inch net width
0.113-inch root radius, r
60° flank angle, ω

Circumferentially notched [Ref. (e)]
1.375-inch gross width
0.25-inch net width
0.13-inch root radius, r
60° flank angle, ω

References: 3.7.10.2.8 (a) through (e)

Surface Condition:
Not specified [Ref. (a) and (b)]
As machined and deburred [Ref. (c)]
32 RMS [Ref. (d)]
10 RMS [Ref. (e)]

Test Parameters:
Loading — Axial
Frequency
— Not specified [Ref. (a) and (b)]
— 1800 cpm [Ref. (c) and (d)]
— 1500 cpm [Ref. (e)]
Temperature — RT
Environment — Air

No. of Heats/Lots: 8

Equivalent Strain Equation:
$\text{Log } N_f = 8.46\text{-}3.21 \log (S_{eq}\text{-}7.5)$
$S_{eq} = S_{max}(1\text{-}R)^{0.72}$
Std. Error of Estimate, Log (Life) = 0.422
Standard Deviation, Log (Life) = 0.923
R^2 = 79%

Sample Size = 97

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

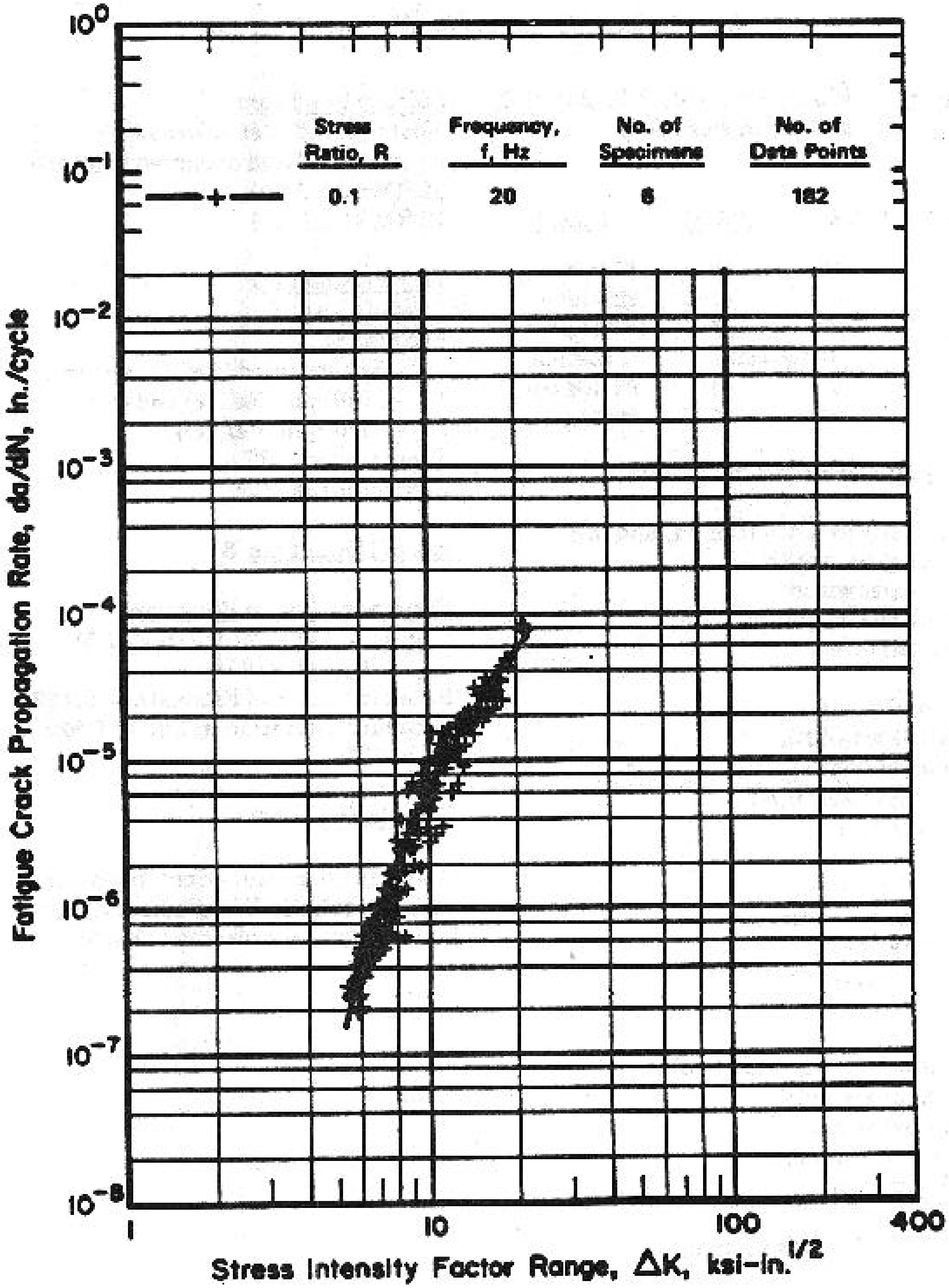

Figure 3.7.10.2.9(a). Fatigue-crack-propagation data for 1.5-inch-thick, 7475-T7351 aluminum alloy plate [References 3.7.10.2.9(a) and (b)].

Specimen Thickness:	*0.650-inch*	*Environment:*	*Lab air*
Specimen Width:	*1.500-inches*	*Temperature:*	*RT*
Specimen Type:	*C(T)*	*Orientation:*	*L-T*

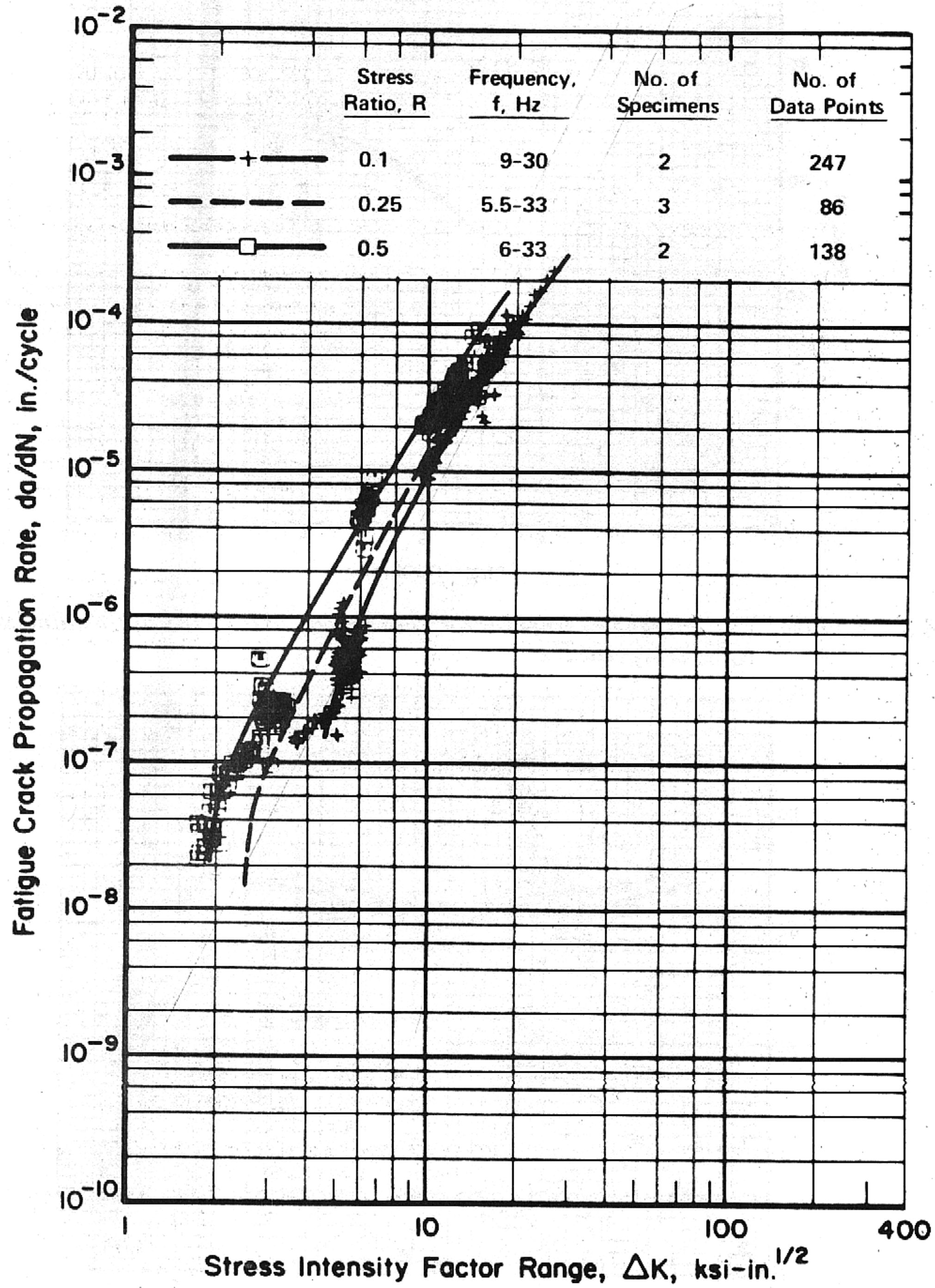

Figure 3.7.10.2.9(b). Fatigue-crack-propagation data for 0.500-inch-thick, 7475-T7351 aluminum alloy plate [Reference 3.7.10.2.9(c)].

Specimen Thickness:	*0.528 to 0.530-inch*	*Environment:*	*95% R.H.*
Specimen Width:	*4.6-inches*	*Temperature:*	*RT*
Specimen Type:	*M(T)*	*Orientation:*	*L-T*

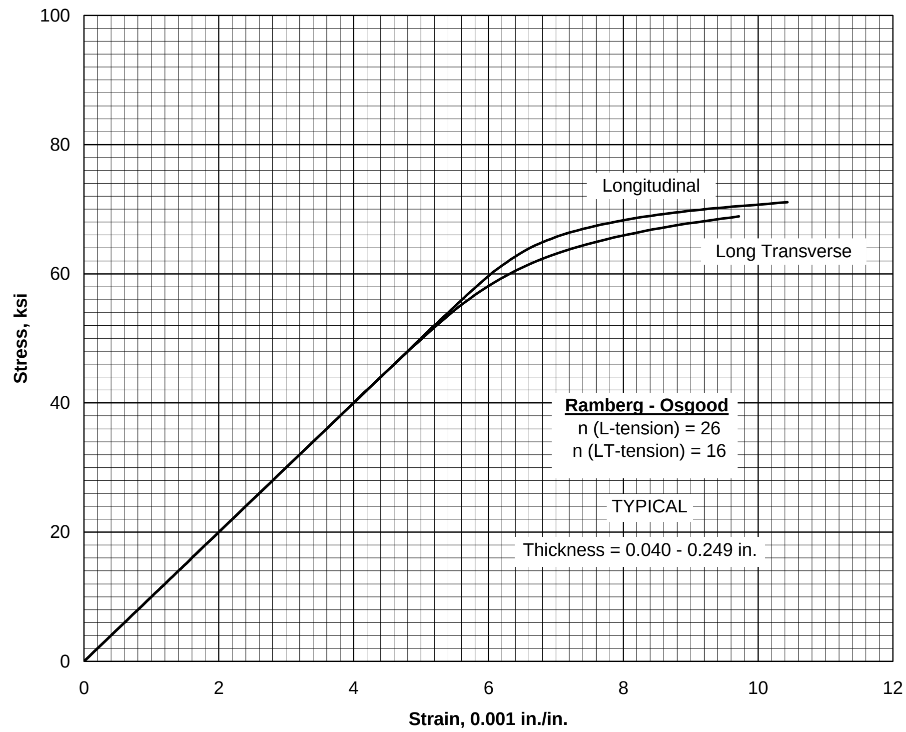

Figure 3.7.10.3.6(a). Typical tensile stress-strain curves for 7475-T761 aluminum alloy sheet at room temperature.

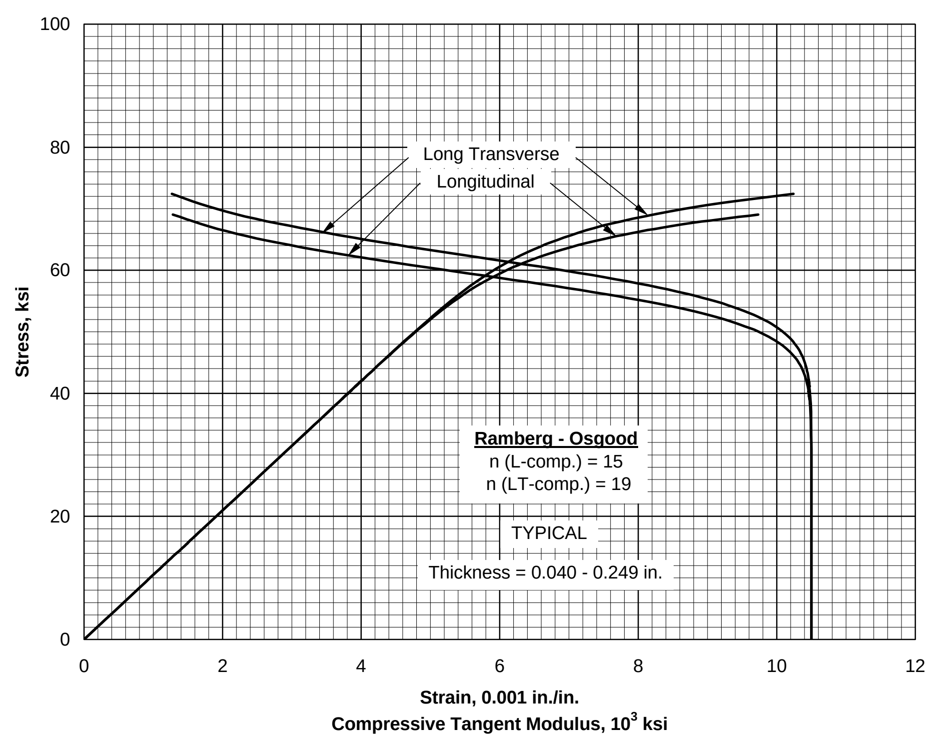

Figure 3.7.10.3.6(b). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T761 aluminum alloy sheet at room temperature.

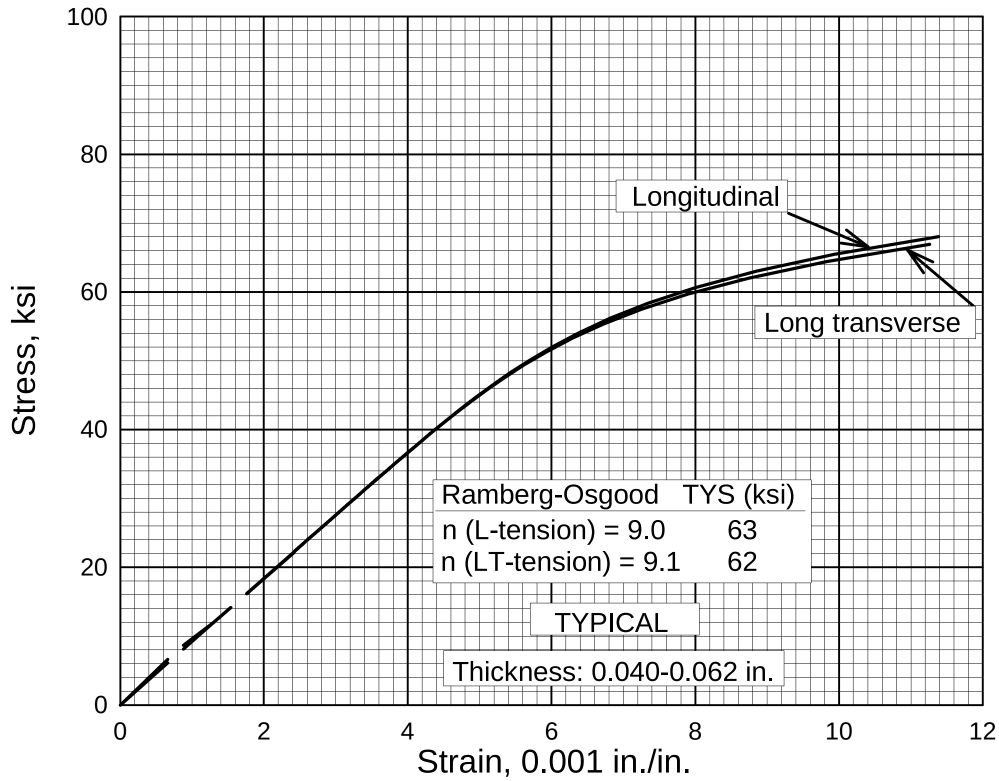

Figure 3.7.10.3.6(c). Typical tensile stress-strain curves for clad 7475-T761 aluminum alloy sheet at room temperature.

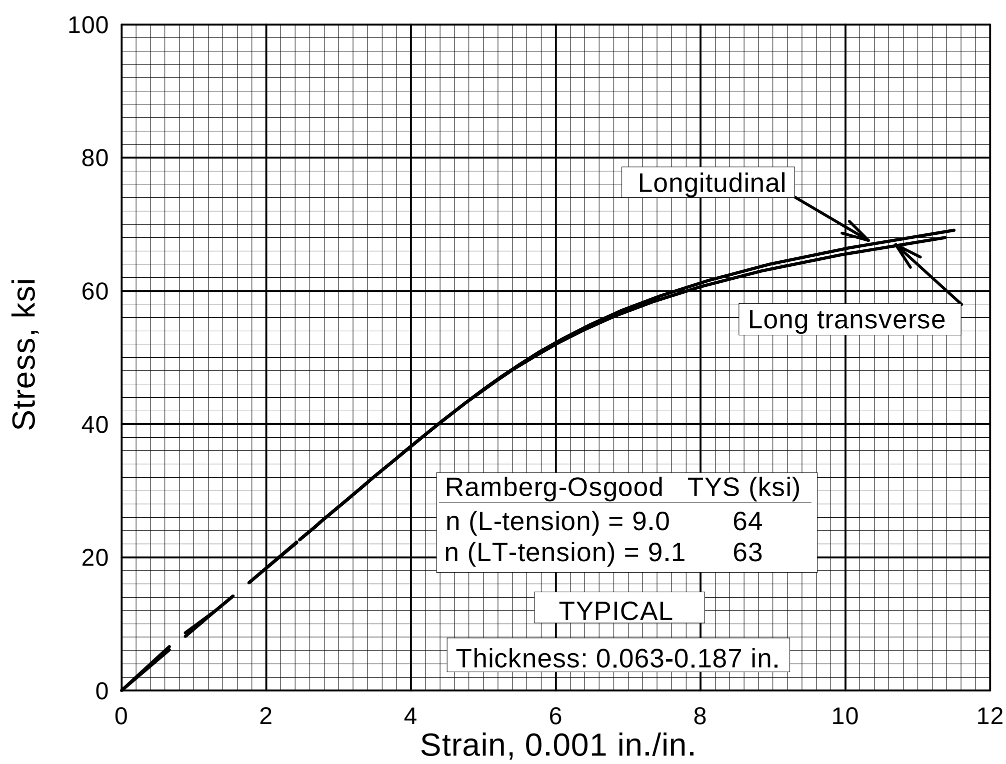

Figure 3.7.10.3.6(d). Typical tensile stress-strain curves for clad 7475-T761 aluminum alloy sheet at room temperature.

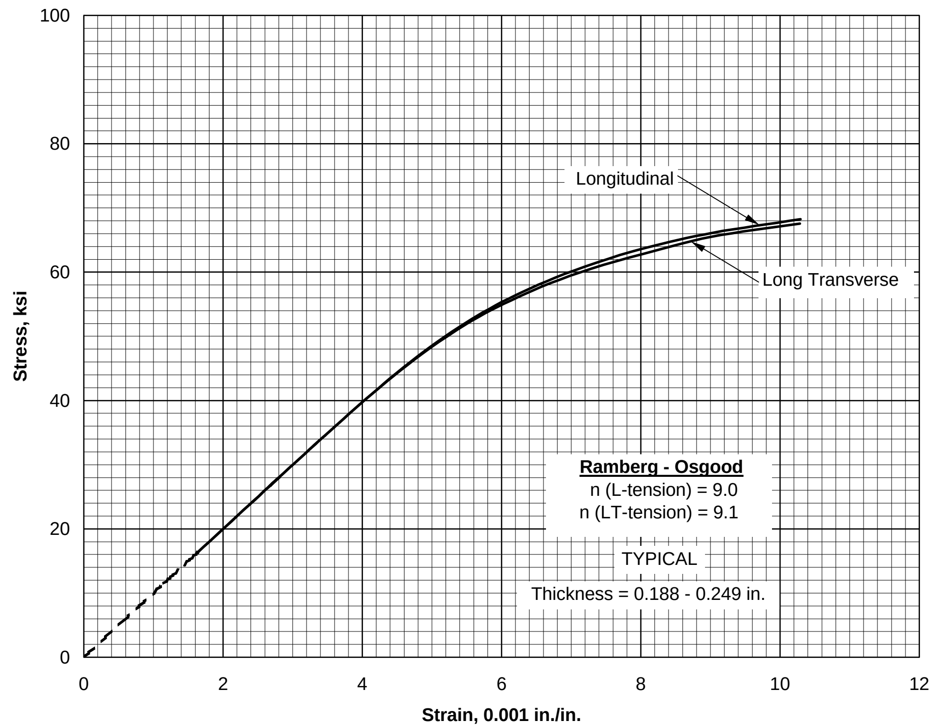

Figure 3.7.10.3.6(e). Typical tensile stress-strain curves for clad 7475-T761 aluminum alloy sheet at room temperature.

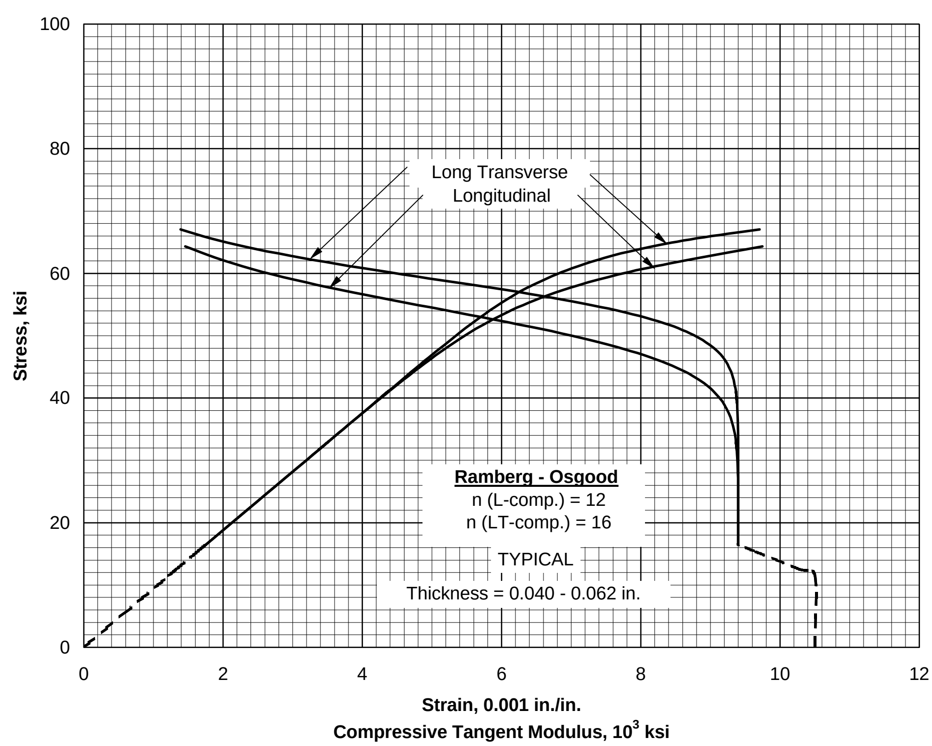

Figure 3.7.10.3.6(f). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T761 aluminum alloy sheet at room temperature.

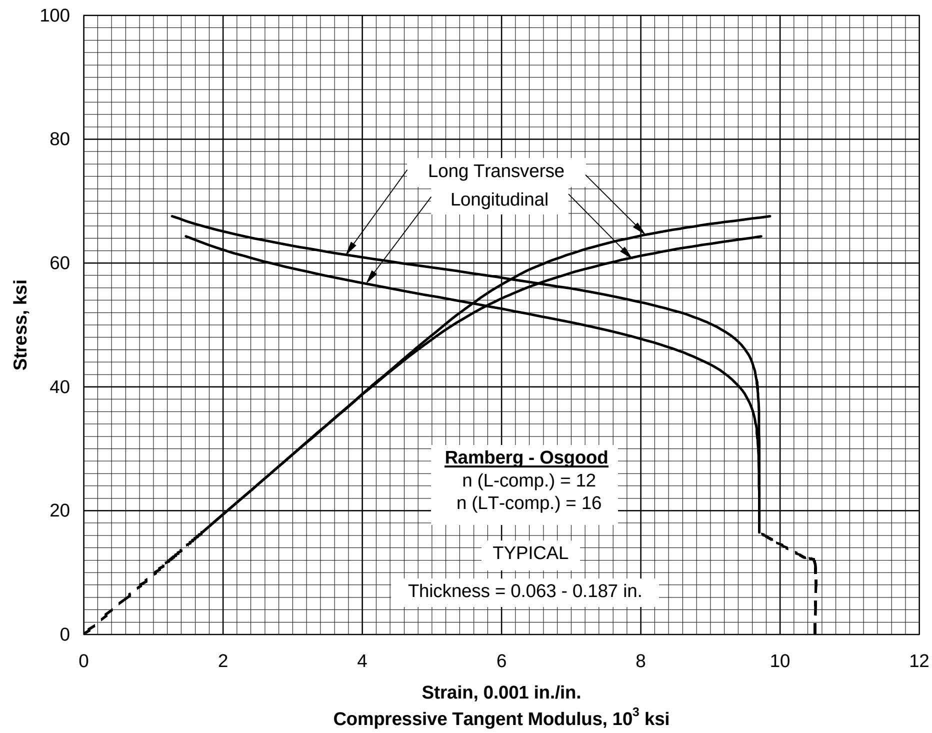

Figure 3.7.10.3.6(g). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T761 aluminum alloy sheet at room temperature.

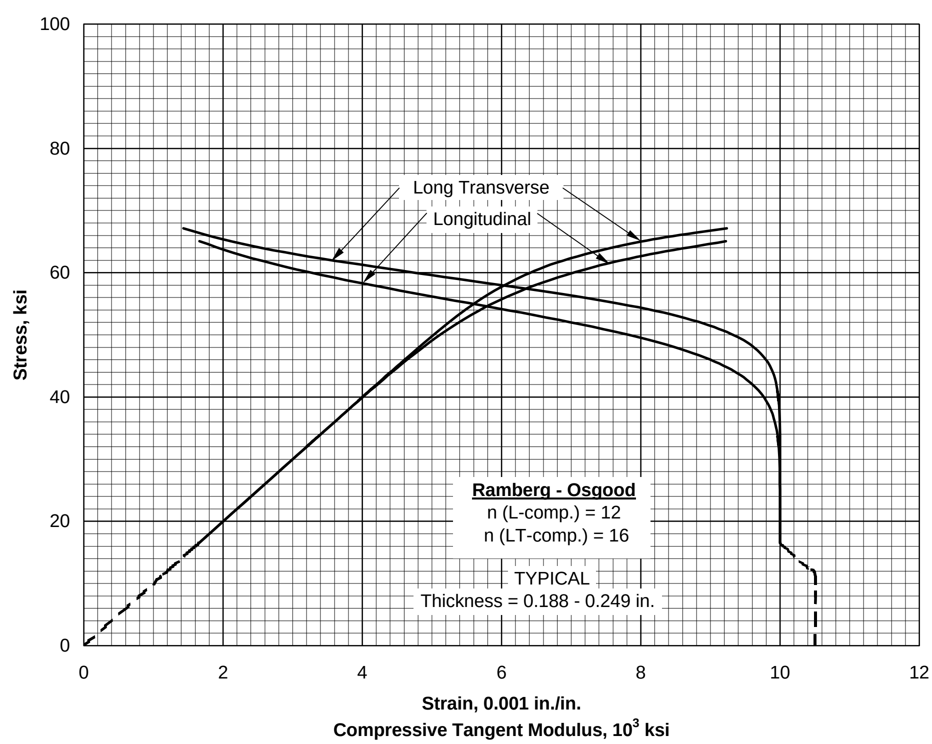

Figure 3.7.10.3.6(h). Typical compressive stress-strain and compressive tangent-modulus curves for clad 7475-T761 aluminum alloy sheet at room temperature.

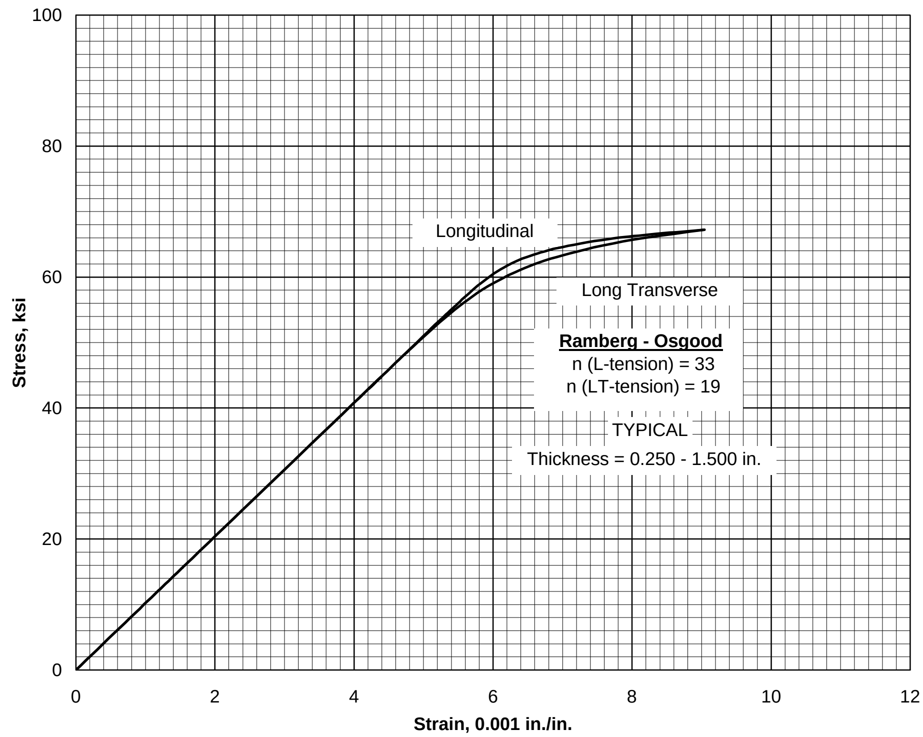

Figure 3.7.10.3.6(i). Typical tensile stress-strain curves for 7475-T7651 aluminum alloy plate at room temperature.

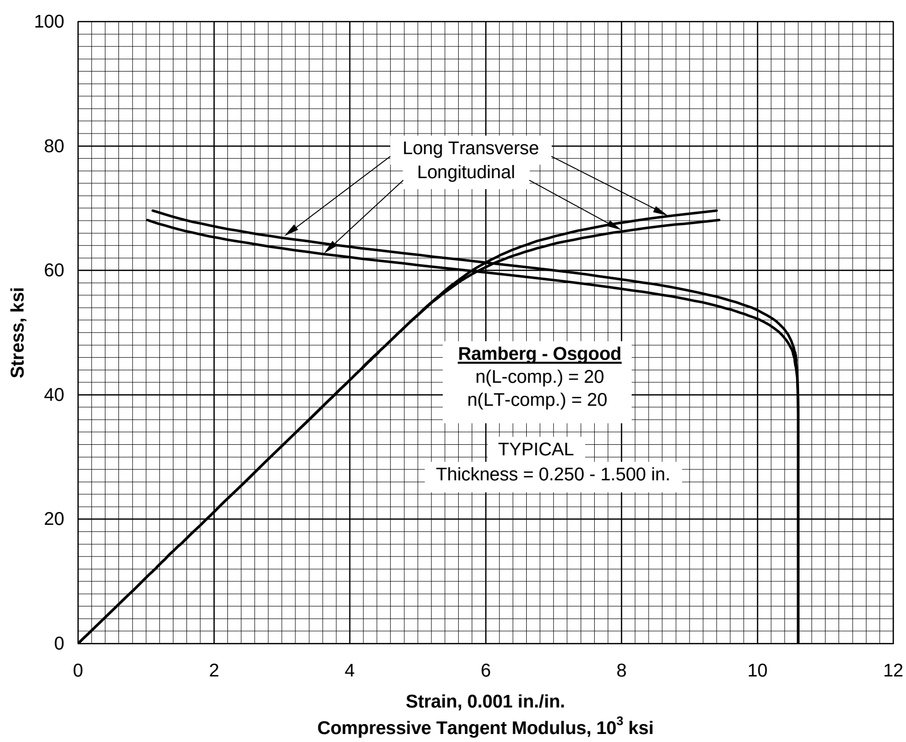

Figure 3.7.10.3.6(j). Typical compressive stress-strain and compressive tangent-modulus curves for 7475-T7651 aluminum alloy plate at room temperature.

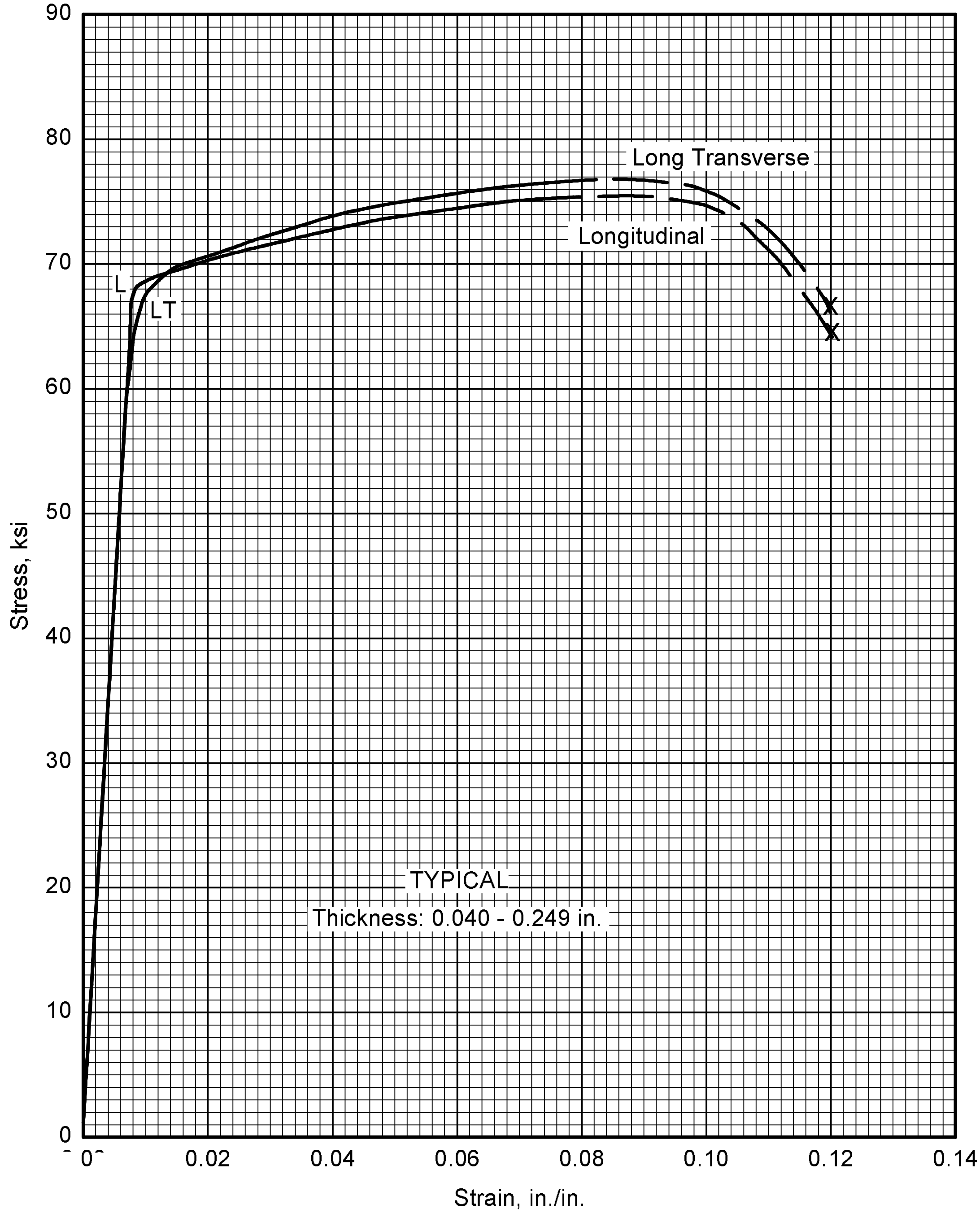

Figure 3.7.10.3.6(k). Typical tensile stress-strain (full range) curves for 7475-T761 aluminum alloy sheet at room temperature.

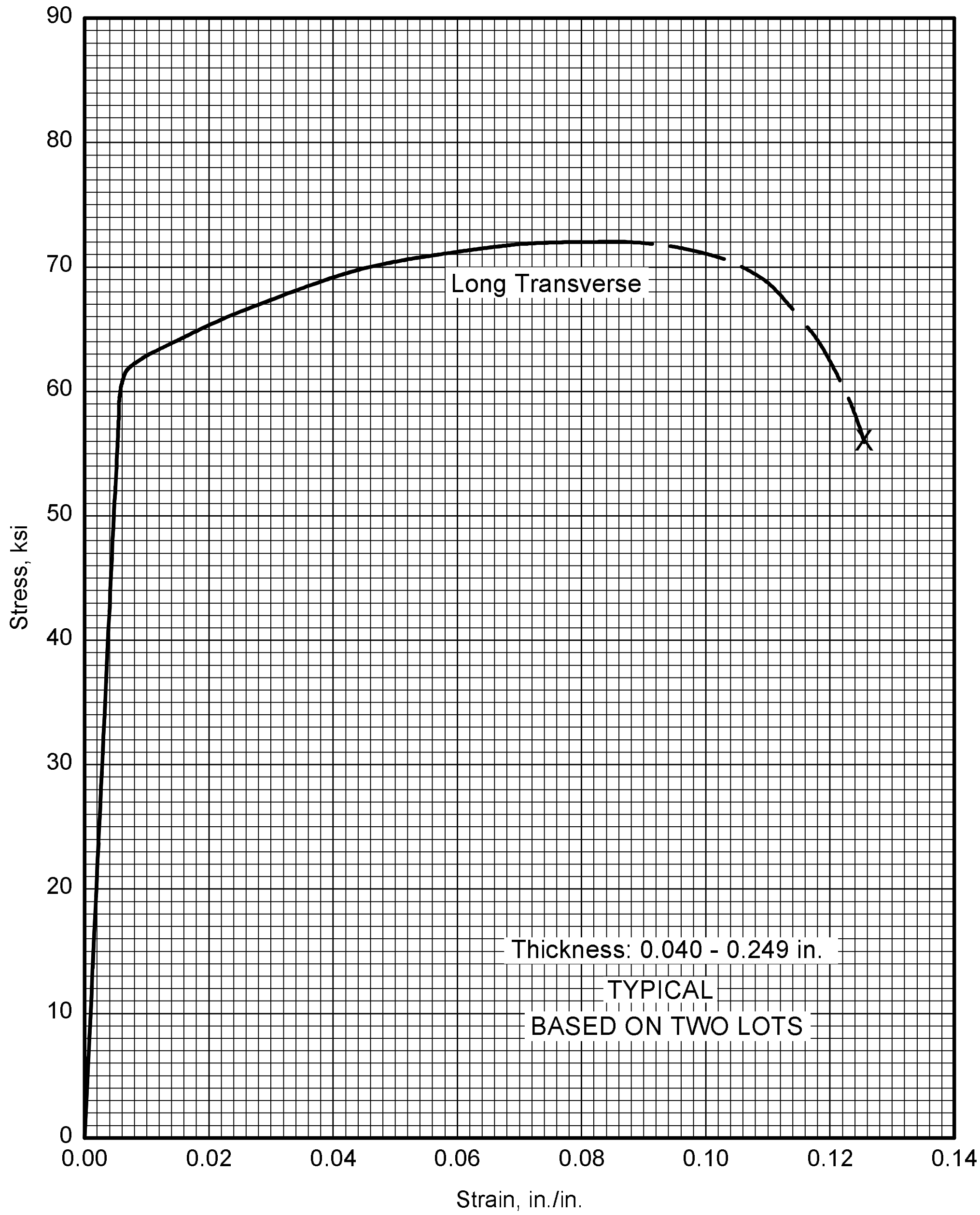

Figure 3.7.10.3.6(l). Typical tensile stress-strain (full range) curves for clad 7475-T761 aluminum alloy sheet at room temperature.

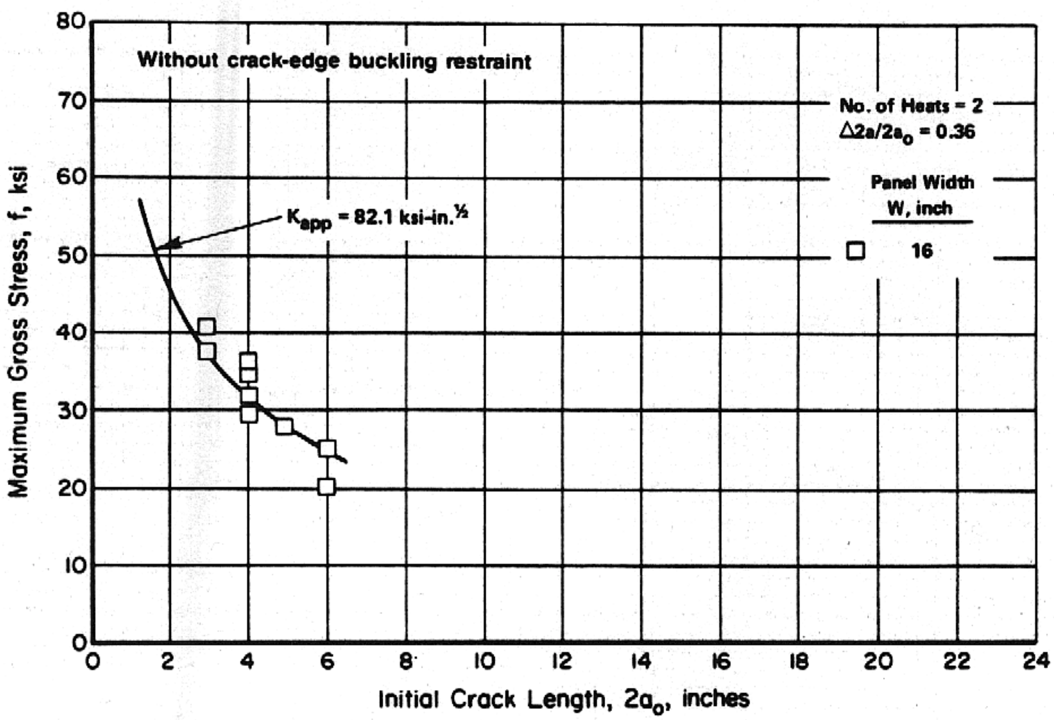

Figure 3.7.10.3.10(a). Residual strength behavior of 0.063-inch-thick 7475-T761 aluminum alloy sheet at room temperature. Crack orientation is L-T. [References 3.1.2.1.6(d) and 3.2.5.1.9(d).]

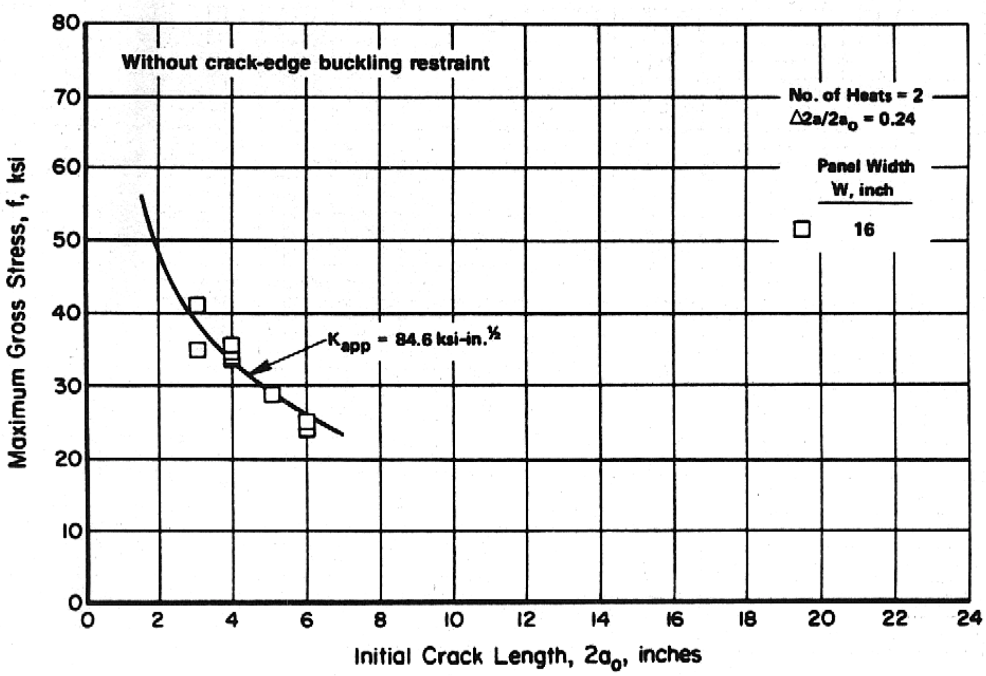

Figure 3.7.10.3.10(b). Residual strength behavior of 0.063-inch-thick 7475-T761 aluminum alloy sheet at room temperature. Crack orientation is T-L. [References 3.1.2.1.6(d) and 3.2.5.1.9(d).]

3.8 200.0 SERIES CAST ALLOYS

Alloys of the 200 series contain copper as the principal alloying element, and are particularly useful for elevated temperature applications.

3.8.1 A201.0 ALLOY

3.8.1.0 *Comments and Properties* — A201.0 is a high-strength, heat-treatable Al-Cu-Ag casting alloy. In the T7 (overaged) temper, it possesses high strength, moderate ductility and optimum resistance to stress-corrosion cracking. Refer to Section 3.1.3.4 for comments regarding the weldability of the alloy.

A material specification covering this alloy is presented in Table 3.8.1.0(a). Room-temperature mechanical and physical properties are presented in Table 3.8.1.0(b). The effect of temperature on thermal expansion is shown in Figure 3.8.1.0.

Table 3.8.1.0(a). Material Specification for A201.0 Aluminum Alloy

Specification	Form
AMS-A-21180	Casting (T7 temper)

The temper index for A201.0 is as follows:

Section	Temper
3.8.1.1	T7

3.8.1.1 *T7 Temper* — Figure 3.8.1.1.6 presents a typical tensile stress-strain curve. Strain control fatigue data are shown in Figures 3.8.1.1.8(a) through (c).

Table 3.9.6.0(b). Design Mechanical and Physical Properties of A357.0 Aluminum Alloy Casting

Specification	AMS-A-21180				
Form	Casting[a]				
Temper	T6				
Location Within Casting	Designated area		Nondesignated area		
Strength Class Number[b]	1	2	10	11	12
Basis	S	S	S	S	S
Mechanical Properties:[c]					
F_{tu}, ksi	45	50	38	41	45
F_{ty}, ksi	35	40	28	31	35
F_{cy}, ksi	35	40	28	31	35
F_{su}, ksi	28	31	24	26	28
F_{bru}[d], ksi:					
(e/D = 1.5)	77	86	65	70	77
(e/D = 2.0)	96	107	81	88	96
F_{bry}[d], ksi:					
(e/D = 1.5)	55	63	44	49	55
(e/D = 2.0)	65	75	52	58	65
e, percent	3	5	5	3	3
E, 10^3 ksi	10.4				
E_c, 10^3 ksi	10.5				
G, 10^3 ksi	3.9				
μ	0.33				
Physical Properties:					
ω, lb/in.^{3}	0.097				
C, Btu/(lb)(°F)	0.23 (at 212°F)				
K, Btu/[(hr)(ft^2)(°F)/ft]	88 (at 77°F)				
α, 10^{-6} in./in./°F	12.0 (68 to 212°F)				

a For any casting process; i.e., special mold, permanent mold, or sand mold (including chilling).
b The attainable strength class number is dependent on the casting configuration, complexity, and size (both weight and wall thickness). Favorable experience with a particular configuration may allow some foundries to produce a higher strength class number than others. In case of doubt regarding the strength class number, the designer should consult or negotiate with the foundry to determine the proper strength class number to assign for a specific casting.
c The mechanical properties shown are reliably obtainable in castings of this alloy and heat-treat condition when produced under the quality assurance provisions of MIL-A-21180. These provisions require preproduction approval, documentation of foundry procedures, and specific destructive and nondestructive testing procedures for the acceptance of each production lot of castings. Strict adherence to these requirements is mandatory if these properties are to be reliably assured in each casting.
d Bearing values are "dry pin" values per Section 1.4.7.1.

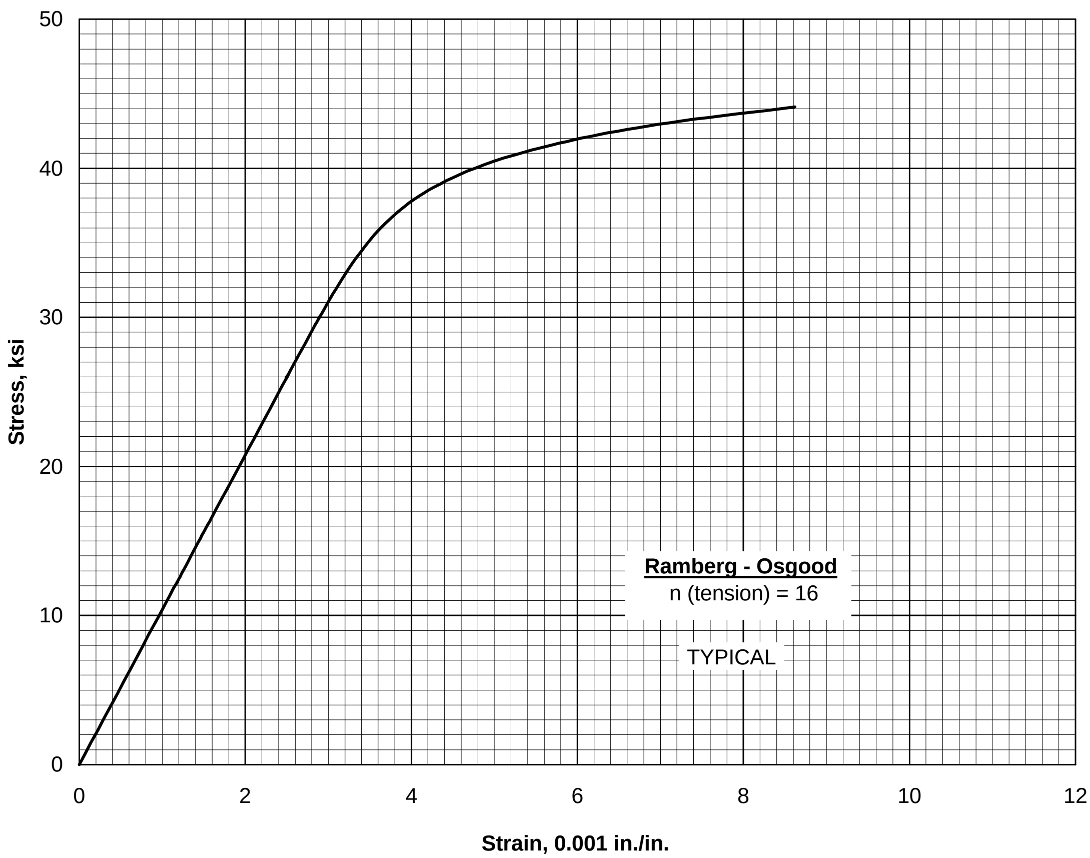

Figure 3.9.6.1.6. Typical tensile stress-strain curve for A357.0-T6 aluminum alloy casting, Class 2, designated area, at room temperature.

Aeronautics and Space Administration, Technical Note D-111 (September 1959) (MIL-HDBK-5 Source M-513).

3.2.3.1.8(h) Naumann, E. C., Hardrath, H. F., and Guthrie, D. E., “Axial-Load Fatigue Tests of 2024-T3 and 7075-T6 Aluminum-Alloy Sheet Specimens Under Constant and Variable Amplitude Loads,” National Aeronautics and Space Administration, Technical Note D-212 (December 1959) (MIL-HDBK-5 Source M-514).

3.2.3.1.8(i) Topper, T. H., and Morrow, J., “Simulation of the Fatigue Behavior at the Notch Root in Spectrum Loaded Notch Member (u),” Naval Air Development Center, Final Report (January 1970).

3.2.5.1.9(a) Pionke, L. J., and Linback, R. K., “Fracture Mechanics Data for 2024-T861 and Aluminum,” NASA CR, MDDC E1153, McDonnell Douglas Astronautics Company (October 25, 1974).

3.2.6.1.9(b) Cervay, R. R., “Temperature Effect on the Mechanical Properties of Aluminum Alloy 2124-T851,” AFML-TR-75-208 (December 1975).

3.2.6.1.9(c) Thompson, D. S., and Zinkham, R. E., “Program to Improve the Fracture Toughness and Fatigue Resistance of Aluminum Sheet and Plate for Airframe Applications,” AFML-TR-73-247, Vol. II (September 1974).

3.2.6.1.9(d) Babilion, C. F., Wygonik, R. H., Nordmark, G. E., and Lifka, B. W., “Mechanical Properties, Fracture Toughness, Fatigue, Environmental Fatigue Crack Growth Rates, and Corrosion Characteristics of High-Toughness Aluminum Alloy Forgings, Sheet, and Plate,” AFML-TR-73-83 (April 1973) (MCIC 86842) (MIL-HDBK-5 Source M-118).

3.2.7.2.8 Ferguson, R. F., “Axial Stress Fatigue Strength of 2219-T851 Aluminum Alloy Plate,” Report No. TFD-71-960, North American Rockwell, Los Angeles Division (July 29, 1971) (MIL-HDBK-5 Source M-216).

3.7.3.1.8(a) Rothweiler, C. E., and Maynard, P. S., “Evaluation of 7049-T73 Aluminum Alloy for RA-5C Wing Inner Panel Fold Rib,” CMES Contract N00256-71-C-0064, Task No. NAR-18 (P046-10), Report No. NR72H-278, North American Rockwell, Columbus, Ohio (July 14, 1972) (MIL-HDBK-5 Source M-170).

3.7.3.1.8(b) Anon., “Boeing Test Data on X7049-T73,” Submitted to Battelle to provide input data for Item 68-24 (1969) (MCIC 78639).

3.7.3.1.8(c) Mixon, W., and Turley, R. V., “Evaluation of Aluminum Alloys 7049-T73 and 7175-T736 Die Forging,” Engineering Technical Report No. ETR-MDC-J0692, McDonnell Douglas (April 7, 1970) (MCIC 110111).

3.7.3.1.8(d) VanOrden, J. M., “Evaluation of 7049-T73 Aluminum Alloy Hand-Forged Billet,” Lockheed California Company, Report No. LR 23447 (February 1970) (MIL-HDBK-5 Source M-43).

3.7.3.1.8(e) “Effect of Manufacturing Processes on Structural Allowables—Phase I,” Battelle, Columbus, Ohio, AFWAL-TR-85-4128 (January 1986).

3.7.4.2.8(a) Guthorn, P. S., "Design Properties and Processing Limits for Improved Aluminum Alloys," McDonnell Douglas Corporation, MDC-J1912 (December 1983) (MIL-HDBK-5 Source M-629).

3.7.4.2.8(b) Garland, K., "Evaluation of X7050-T736 Die Forgings," McDonnell Aircraft Company, McDonnell Douglas Corporation, Report No. 514-131.10 (February 1973) (MCIC 85880).

3.7.4.2.8(c) Deel, O. L., Ruff, P. E., and Mindlin, H., "Engineering Data on New Aerospace Structural Materials," AFML-TR-114 (June 1973) (MIL-HDBK-5 Source M-467).

3.7.4.2.8(d) Gallo, K. L., "Load Control Fatigue Data Reports," Westmoreland Mechanical Testing and Research, Inc., March 1997.

3.7.4.2.8(e) Deschapelles, J. B., "Improved Fatigue Resistance of 7050 Thick Plate Aluminum Through Minimization of Microporosity," Effects of Product Quality and Design Criteria on Structural Integrity, ASTM STP 1337, R. C. Rice and D. E. Tritsch, Eds., American Society for Testing and Materials, 1998.

3.7.4.2.9(a) Northrop, attachments to letter from V. C. Frost to D. J. Jones (March 4, 1981) (MIL-HDBK-5 Source M-482).

3.7.4.2.9(b) Davis, R. E., Nordmark, G. E., and Walsh, J. D., "Design Mechanical Properties, Fracture Toughness, Fatigue Properties, Exfoliation, and Stress-Corrosion Resistance of 7050 Sheet, Plate, Hand Forgings, Die Forgings, and Extrusions," Report N00019-72-C-0512, Aluminum Company of America (July 1975) (MIL-HDBK-5 Source M-322).

3.7.4.3.8(a) Staley, J. T., Jacoby, J. E., Davies, R. E., Nordmark, G. E., Walsh, J. D., and Rudolph, F. R., "Aluminum Alloy 7050 Extrusions," AFML-TR-76-129 (March 1977) (MCIC 99225) (MIL-HDBK-5 Source M-374).

3.7.6.1 Brownfield, C. D., and Badger, D. M., "Effects of Temperature-Time-Stress Histories on the Mechanical Properties of Aircraft Structural Metallic Materials," WADC TR 56-585, Part II (September 1960).

3.7.6.1.8 Howell, F. M., and Miller, J. L., "Axial Fatigue Strengths of Several Structural Aluminum Alloys," Proceedings of the American Society for Testing Materials, Philadelphia, PA (1956).

3.7.6.1.9(a) Hudson, C. M., and Hardrath, H. F., "Effects of Changing Stress Amplitude on the Rate of Fatigue-Crack-Propagation in Two Aluminum Alloys," National Aeronautics and Space Administration, Technical Note D-960 (1961).

3.7.6.1.9(b) McEvily, A. J., and Ilig, W., "The Rate of Fatigue-Crack Propagation in Two Aluminum Alloys," National Aeronautics and Space Administration, Technical Note 4394 (1958).

3.7.6.1.9(c) Brock, D., and Schijve, J., "The Influence of Mean Stress on the Propagation of Fatigue Cracks in Aluminum Alloy Sheet," NLR-TR, M. 2111, Reports and Transactions, National Aero- and Astronautical Research Institute, pp. 41-61 (1965).

3.7.6.1.9(d) Dubensky, R. G., "Fatigue-Crack Propagation in 2024-T3 and 7075-T6 Aluminum Alloys at High Stresses," NASA CR-1732 (1971).

3.7.6.1.9(e) Hudson, C. M., "Effect of Stress Ratios on Fatigue-Crack Growth in 7075-T6 and 2024-T3 Aluminum Alloy Specimens," National Advisory Committee for Aeronautics, Technical Note D-5390 (August 1969) (MCIC 75599).

3.7.6.1.9(f) Gurin, P. J., "Crack Propagation Tests for Some Aluminum Alloy Materials," LR 10498, Lockheed Aircraft Corporation (1955).

3.7.6.2.9(a) Unpublished Battelle, Columbus, Ohio data by C. F. Fedderson.

3.7.6.2.9(b) "B-1 Program Data for Aluminum Alloys," Rockwell International Corporation, Memorandum to H. D. Moran from E. W. Cawthorne, Battelle, Columbus, Ohio (April 3, 1974) (MCIC 88579).

3.7.6.2.9(c) Ruff, P. E., and Smith, S. H., "Development of MIL-HDBK-5 Design Allowable Properties and Fatigue-Crack-Propagation Data for Several Aerospace Materials," AFML-TR-77-162 (October 1977).

3.7.7.2.8 Unpublished Letter to D. Lahrman, Battelle, from Alcoa, "Fatigue Properties of 7150-T77511 Extruded Shapes." (December 9, 1993) (MIL-HDBK-5 Source M-798).

3.7.8.1.8(a) Unpublished Letter to P. Ruff, Battelle Memorial Institute, from Lockheed-Georgia, "Fatigue Data on 7175-T7351 Extrusions," January 1982.

3.7.8.1.8(b) Carter, F. J., Bateh, E. J., and White, D. L., "C-5A Wing Modification Program, Material Characterization Program, 7175-T7511 Extrusions," Lockheed-Georgia Company, Report No. LG75ER0186-2, September 1977 (MCIC 122032).

3.7.8.1.8(c) Unpublished Letter to P. Ruff, Battelle Memorial Institute, from Aluminum Company of America, "Fatigue Data on 7175-T73511 Extrusions and 7175-T74 Forgings," January 24, 1990 (MIL-HDBK-5 Source M-748).

3.7.8.2.8(a) Schimmelbusch, H. W., "Metallurgical Evaluation of 7175-T736 and 7175-T66 Die Forgings," Boeing Company Document No. D6-24480, May 1970 (MCIC 78656).

3.7.8.2.8(b) Newcomer, R., "Evaluation of Aluminum Forging Alloy 7175-T736," McDonnell Aircraft Company Report No. MDC 70-024, 1970 (MCIC 85881).

3.7.8.2.8(c) Deel, O. L., and Mindlin, H., "Engineering Data on New and Emerging Structural Materials," AFML Report No. AFML-TR-70-252, October 1970 (MIL-HDBK-5 Source M-464).

3.7.10.2.8(d) Doepker, P., "Effect of Manufacturing Process on Structural Allowables," AFWAL Report No. AFWAL-TR-85-4049 (MIL-HDBK-5 Source M-626).

3.7.10.2.8(a) Brownhill, D. J., Davies, R. E., Nordmark, G. E., and Ponchel, B. M., "Exploratory Development for Design Data on Structural Aluminum Alloys in Representative Aircraft Environments," AFML-TR-77-102 (July 1977) (MCIC 103463) (MIL-HDBK-5 Source M-397).

3.7.10.2.8(b) Unpublished letter to P. Vieth, Battelle, Columbus, Ohio from ALCOA, "Fatigue Data for 7050 and 7475 Products" (July 17, 1985) (MIL-HDBK-5 Source M-630).

3.7.10.2.8(c) Jones, R. L., and Coyle, T. E., "The Mechanical Stress Corrosion, Fracture Mechanics, and Fatigue Properties of 7050, 7475, and Ti-8Mo-8V-2Fe-3Al Plate and Sheet Alloys," General Dynamics, Report No. FGT-5791 (July 24, 1973) (MCIC 100670).

3.7.10.2.8(d) Figge, F. A., "Advanced Metallic Structure: Air Superiority Fighter Wind Design for Improved Cost, Weight, and Integrity," AFFDL-TR-73-52, Vol. III (June 1973) (MCIC 86574) (MIL-HDBK-5 Source M-278).

3.7.10.2.8(e) Deel, O. L., Ruff, P. E., and Mindlin, H., "Engineering Data on New Aerospace Structural Materials," AFML-TR-75-97 (June 1975) (MCIC 95044) (MIL-HDBK-5 Source M-468).

3.7.10.2.9(a) Cervay, R. R., "Engineering Design Data for Aluminum Alloy 7475 in the T761 and T61 Conditions," AFML-TR-72-173 (September 1972) (MCIC 85363).

3.7.10.2.9(b) Cervay, R. R., "Static and Dynamic Fracture Properties for Aluminum Alloy 7475-T651 and T7351," AFML-TR-75-20 (April 1975).

3.8.1.1.8(a) Unpublished data from Garrett Turbine Engine Company, 1986 (MIL-HDBK-5 Source M-690).

3.8.1.1.8(b) Unpublished data from Northrop Corporation, 1988 (MIL-HDBK-5 Source M-701).

3.11.1.2 Eato, I. D., and Holt, M., "Flexural Fatigue Strengths of Riveted Box Beams—Alclad 14S-T6, Alclad 75S-T6, and Various Tempers of Alcald 24S," National Advisory Committee for Aeronautics, Technical Note 2452, 25 pp. (November 1951).

3.11.2.2(a) Gerard, G., and Becker, H., Handbook of Structural Stability, "Part I—Buckling of Flat Plates," National Advisory Committee for Aeronautics, Technical Note 3781 (July 1957).

3.11.2.2(b) Becker, H., Handbook of Structural Stability, "Part II—Buckling of Composite Elements," National Advisory Committee for Aeronautics, Technical Note 3782 (July 1957).

3.11.2.2(c) Gerard, G., and Becker, H., Handbook of Structural Stability, "Part III—Buckling of Curved Plates and Shells," National Advisory Committee for Aeronautics, Technical Note 3783 (1957).

3.11.2.2(d) Gerard, G., Handbook of Structural Stability, "Part IV—Failure of Plates and Composite Elements," National Advisory Committee for Aeronautics, Technical Note 3784 (1957).

3.11.2.2(e) Gerard, G., Handbook of Structural Stability, "Part V—Compressive Strengths of Flat Stiffened Panels," National Advisory Committee for Aeronautics, Technical Note 3785 (August 1957).

CHAPTER 4

MAGNESIUM ALLOYS

4.1 GENERAL

This chapter contains the engineering properties and characteristics of wrought and cast magnesium alloys used in aircraft and missile applications. Magnesium is a lightweight structural metal that can be strengthened greatly by alloying, and in some cases by heat treatment or cold work or by both.

4.1.1 ALLOY INDEX — The magnesium alloys in this chapter are listed in alphanumeric sequence in each of two parts, the first one being wrought forms of magnesium and the second cast forms. These sections and the alloys covered under each are shown in Table 4.1.

Table 4.1. Magnesium Alloys Index

Section	Designation
4.2	**Magnesium-Wrought Alloys**
4.2.1	AZ31B
4.2.2	AZ61A
4.2.3	ZK60A
4.3	**Magnesium-Cast Alloys**
4.3.1	AM100A
4.3.2	AZ91C/AZ91E
4.3.3	AZ92A
4.3.4	EZ33A
4.3.5	QE22A
4.3.6	ZE41A

4.1.2 MATERIAL PROPERTIES

4.1.2.1 *Mechanical Properties* — The mechanical properties are given either as design values or for information purposes. The tensile strength (F_{tu}), tensile yield strength (F_{ty}), elongation (e), and sometimes the compressive yield strength (F_{cy}) are guaranteed by procurement specifications. The properties obtained reflect the location of sample, type of test specimen and method of testing required by the product specification. The remaining design values are "derived" values; that is, sufficient tests have been made to ascertain that if a given material meets the requirements of the product specification, the material will have the compression (F_{cy}), shear (F_{su}) and bearing (F_{bru} and F_{bry}) strengths listed.

4.1.2.1.1 *Tension Testing* — Room-temperature tension tests are made according to ASTM E 8. The yield strength (F_{ty}) is obtained by the "offset method" using an offset of 0.2 percent. The speed of testing for room-temperature tests has a small effect on the strength and elongation values obtained on most magnesium alloys. The rate of stressing generally specified to the yield strength is less than 100,000 psi per minute and the rate of straining from the yield strength to fracture is less than 0.5 in./in./min. It can be expected that the speed of testing used for room-temperature tension tests will approach the maximum permitted.

Elevated-temperature tension tests are made according to ASTM E 21. The speed of testing has a considerable effect on the results obtained and no one standard rate of straining is given in ASTM E 21. The strain rates most commonly used on magnesium are 0.005 in./in./min. to the yield and 0.10 in./in./min. from yield to fracture [see References 4.1.2.1.1(a) to (d)].

4.1.2.1.2 *Compression Testing* — Compression test methods used for magnesium are specified in ASTM E 9. The values given for the compressive yield strength (F_{cy}), are taken at an offset of 0.2 percent. References 4.1.2.1.2(a) and (b) provide information on test techniques.

4.1.2.1.3 *Bearing Testing* — Bearing tests of magnesium alloys are made according to ASTM E 238. The size of pin used has a significant effect on the values obtained, especially the bearing ultimate strength (F_{bru}). On tests made to obtain the data on magnesium alloys shown in this document, pin diameters of 0.187 and 0.250 inch were used. For pin diameters significantly larger than 0.250 inch lower values may be obtained. Additional information on bearing testing is given in References 4.1.2.1.3(a) and (b). Bearing values in the property tables are considered to be "dry pin" values in accordance with the discussion in Section 1.4.7.1.

4.1.2.1.4 *Shear Testing* — The shear strength values used in this document were obtained by the "double shear" method using a pin-type specimen, the "punch shear" method and the "tension shear" method as applicable. Just as tensile ultimate strength (F_{tu}) values vary with location and direction of sample in relation to the method of fabrication, the shear strength (F_{su}) may be expected to reflect the effect of orientation, either as a function of the sampling or the maximum stresses imposed by the method of test. Information on shear testing is given in Reference 4.1.2.1.4.

4.1.2.1.5 *Stress Raisers* — The effect of notches, holes, and stress raisers on the static properties of magnesium alloys is described in References 4.1.2.1.5(a) through (c). Additional data on the strength properties of magnesium alloys are presented in References 4.1.2.1.5(d) through (h).

4.1.2.1.6 *Creep* — Some creep data on magnesium alloys are summarized in Reference 4.1.2.1.6.

4.1.2.1.7 *Fatigue* — Room-temperature axial load fatigue data for several magnesium alloys are presented in appropriate alloy sections. References 4.1.2.1.7(a) and (b) provide additional data on fatigue of magnesium alloys.

4.1.3 PHYSICAL PROPERTIES — Selected experimental data from the literature were used in determining values for physical properties. In other cases, enough information was available to calculate the constants. Estimated values of some of the remaining constants were also included. Estimated values are noted.

4.1.4 ENVIRONMENTAL CONSIDERATIONS — Corrosion protection must be considered for all magnesium applications. Protection can be provided by anodic films, chemical conversion coatings, paint systems, platings, or a combination of these methods. Proper drainage must be provided to prevent entrapment of water or other fluids. Dissimilar metal joints must be properly and completely insulated, including barrier strips and sealants.

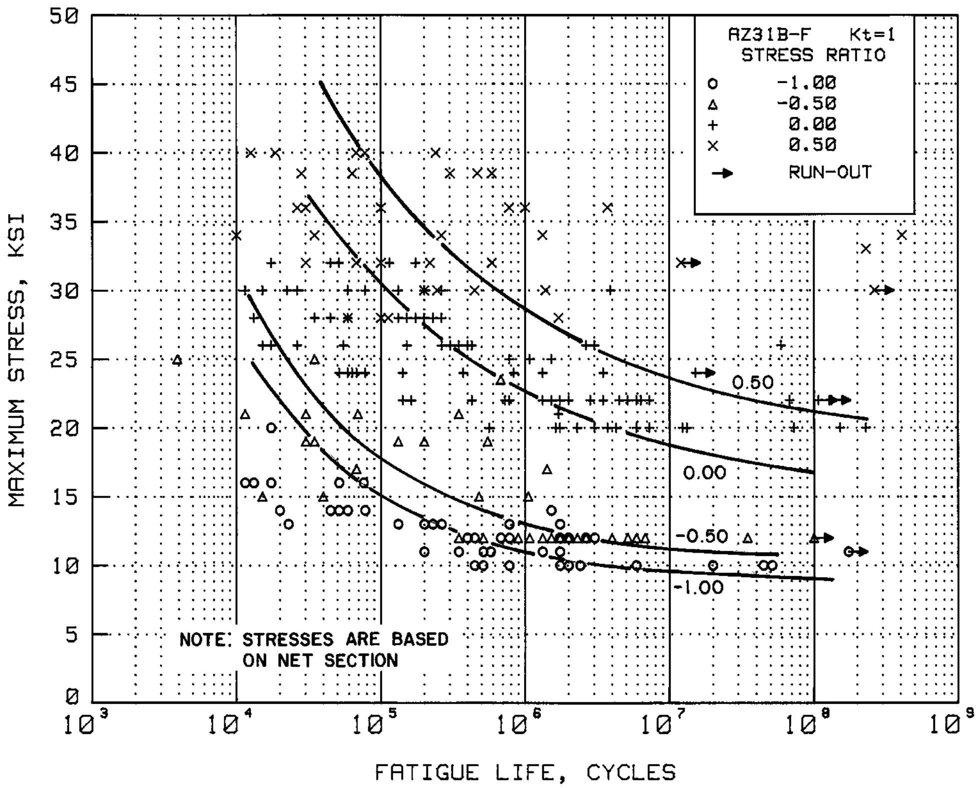

Figure 4.2.1.4.8(a). Best-fit S/N curves for unnotched AZ31B-F magnesium alloy forged disk, transverse direction.

Correlative Information for Figure 4.2.1.4.8(a)

Product Form: Forged disk, 1-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
38	26	RT

Specimen Details: Unnotched
0.75-inch gross diameter
0.30-inch net diameter

Surface Condition:

Polished sequentially with No. 320 aluminum oxide cloth, No. 0, 00, and 000 emery paper and finally No. 600 aluminum oxide powder in water

References: 4.2.1.1.8

Test Parameters:

Loading - Axial
Frequency - 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Equivalent Stress Equation:

For R values between -1.0 and -0.50
$\text{Log } N_f = 7.13\text{-}2.20 \log (S_{eq}\text{-}12.9)$
$S_{eq} = S_{max}(1\text{-}R)^{0.56}$
Standard Error of Estimate = 0.613
Standard Deviation in Life = 0.916
R^2 = 55.2%

For R values between 0.0 and 0.50
$\text{Log } N_f = 8.87\text{-}3.26 \log (S_{eq}\text{-}15.0)$
$S_{eq} = S_{max}(1\text{-}R)^{0.33}$
Standard Error of Estimate = 0.829
Standard Deviation in Life = 1.014
R^2 = 33.2%

Sample Size = 194

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

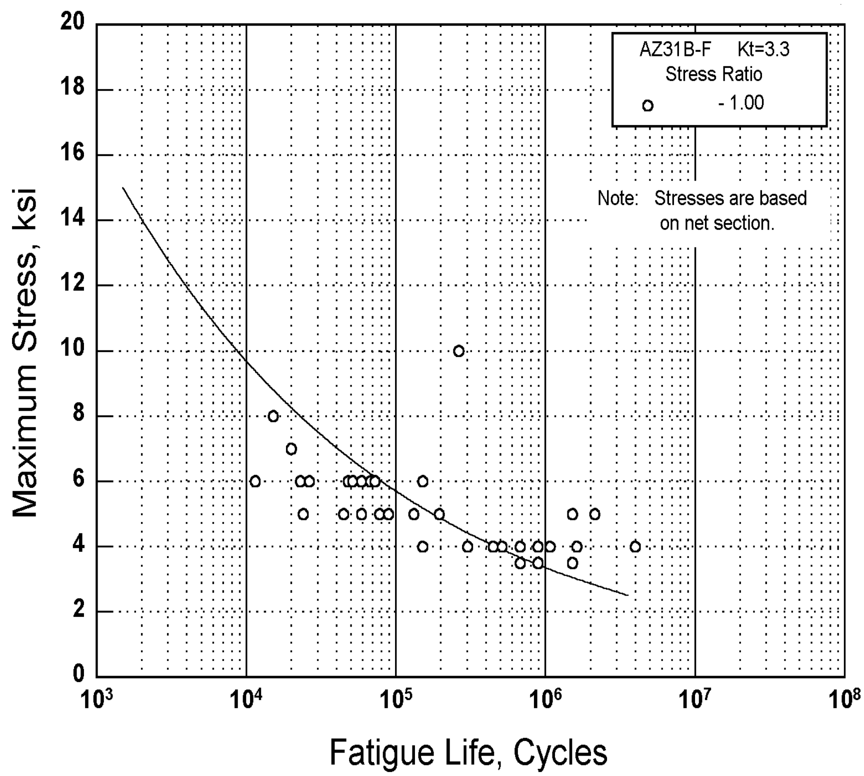

Figure 4.2.1.4.8(b). Best-fit S/N curves for notched, K_t = 3.3, AZ31B-F magnesium alloy forged disk, transverse direction.

Correlative Information for Figure 4.2.1.4.8(b)

Product Form: Forged disk, 1-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
38	26	RT

Specimen Details: Notched, K_t = 3.3
0.350-inch gross diameter
0.280-inch net diameter
0.01-inch root radius, r
60° flank angle, ω

Reference: 4.2.1.1.8

Test Parameters:
Loading - Axial
Frequency - 1500 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: 1

Maximum Stress Equation:

$\text{Log } N_f = 8.28 - 4.34 \log (S_{max})$
Std. Error of Estimate, Log (Life) = 0.534
Standard Deviation, Log (Life) = 0.707
R^2 = 43%

Sample Size = 34

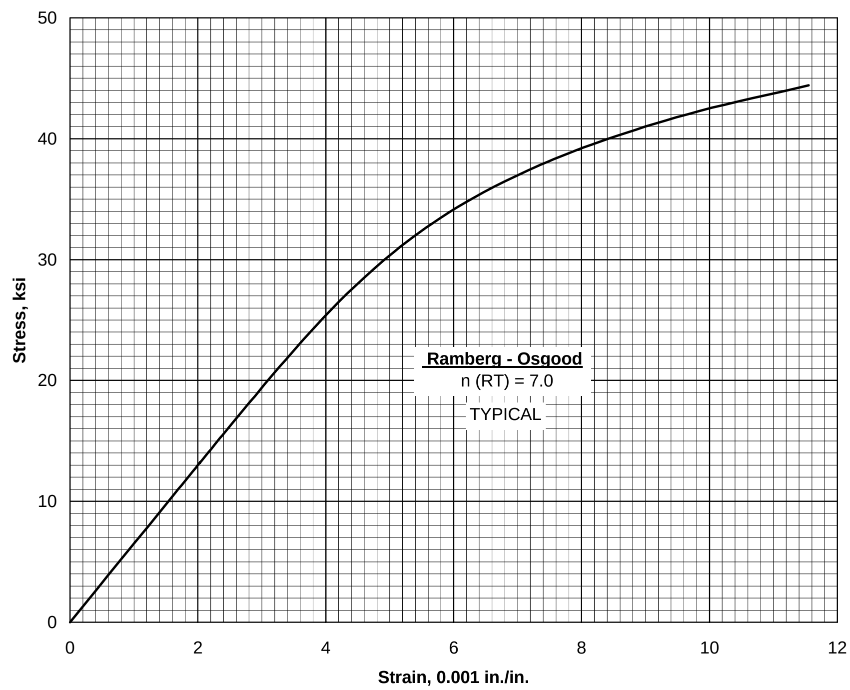

Figure 4.2.3.2.6(a). Typical tensile stress-strain curve for ZK60A-T5 extrusion at room temperature.

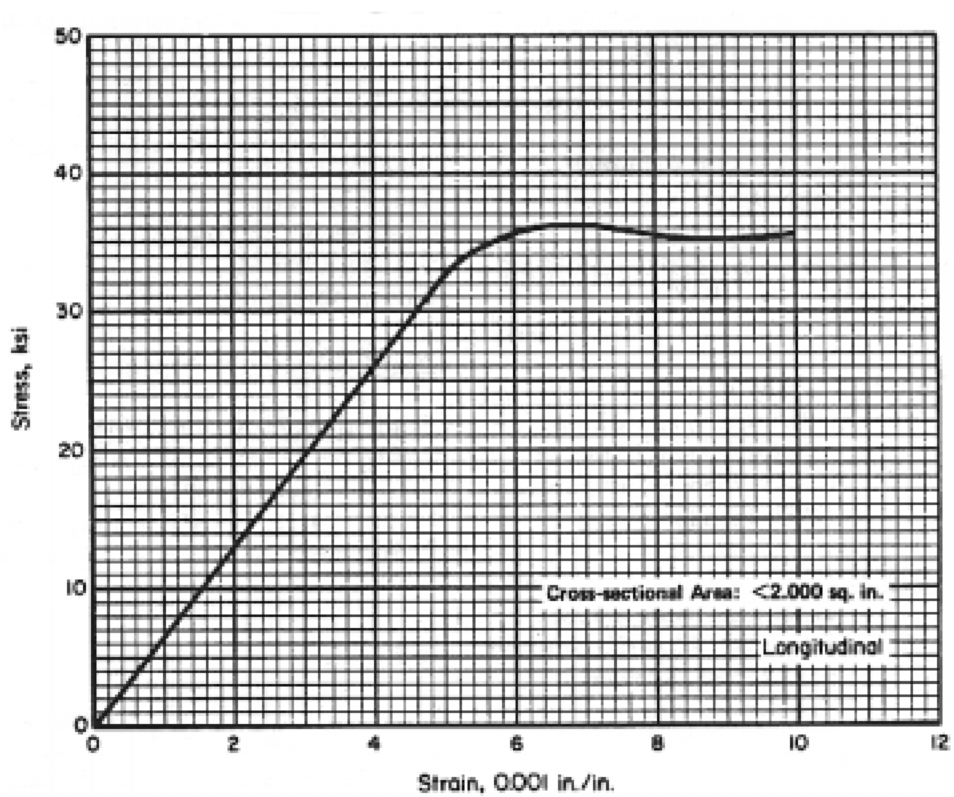

Figure 4.2.3.2.6(b). Typical compressive stress-strain curve for ZK60A-T5 extrusion at room temperature.

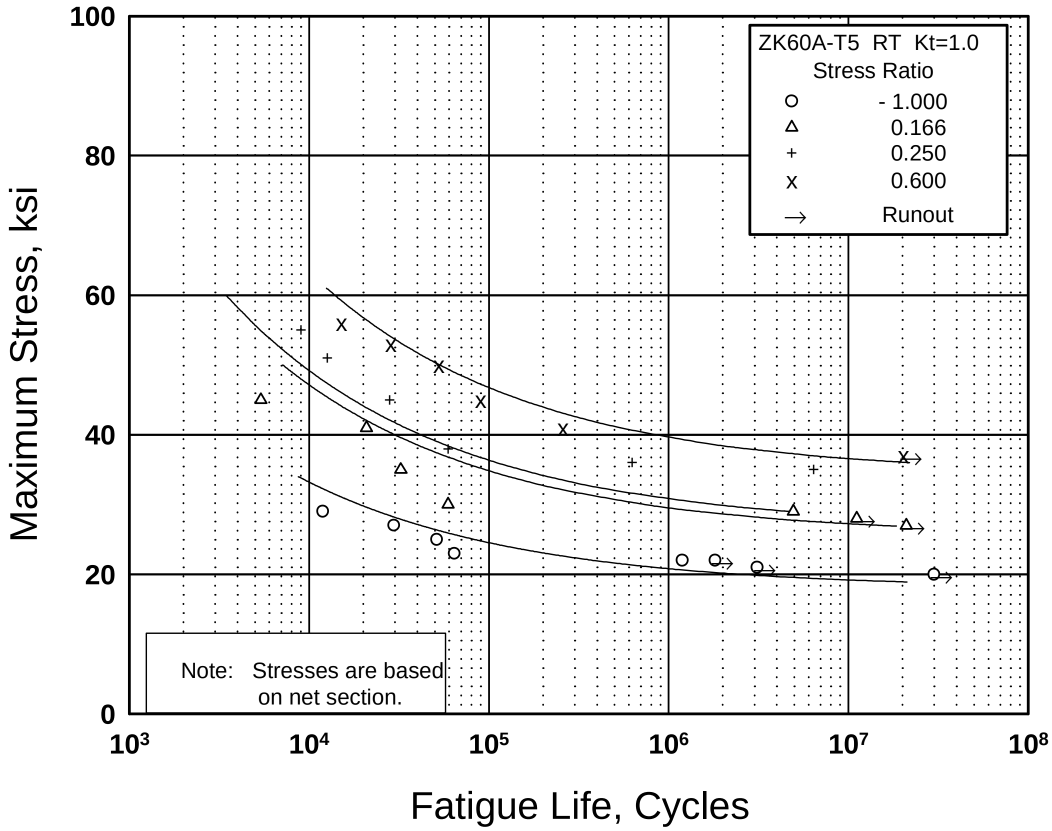

Figure 4.2.3.2.8(a). Best-fit S/N curves for unnotched ZK60A-T5 extruded bar, longitudinal direction.

Correlative Information for Figure 4.2.3.2.8(a)

Product Form: Extruded bar, 0.50-inch diameter

Properties:

TUS, ksi	TYS, ksi	Temp.,°F
47.5	40.9	RT (unnotched)

Specimen Details: Unnotched
0.50-inch gross diameter
0.40-inch net diameter
0.750-inch root diameter
7.50-inch long

Surface Condition: Polished with No. 240 grit aluminum oxide belt and then a No. 400 grit; polished with kerosene to better than 10 micro-inches

Reference: 4.2.3.2.8

Test Parameters:
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:
$\text{Log } N_f = 7.56\text{-}2.73 \log (S_{eq}\text{-}23.7)$
$S_{eq} = S_{max}(1\text{-}R)^{0.40}$
Std. Error of Estimate, Log (Life) = 0.60
Standard Deviation, Log (Life) = 0.85
R^2 = 51%

Sample Size = 21

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

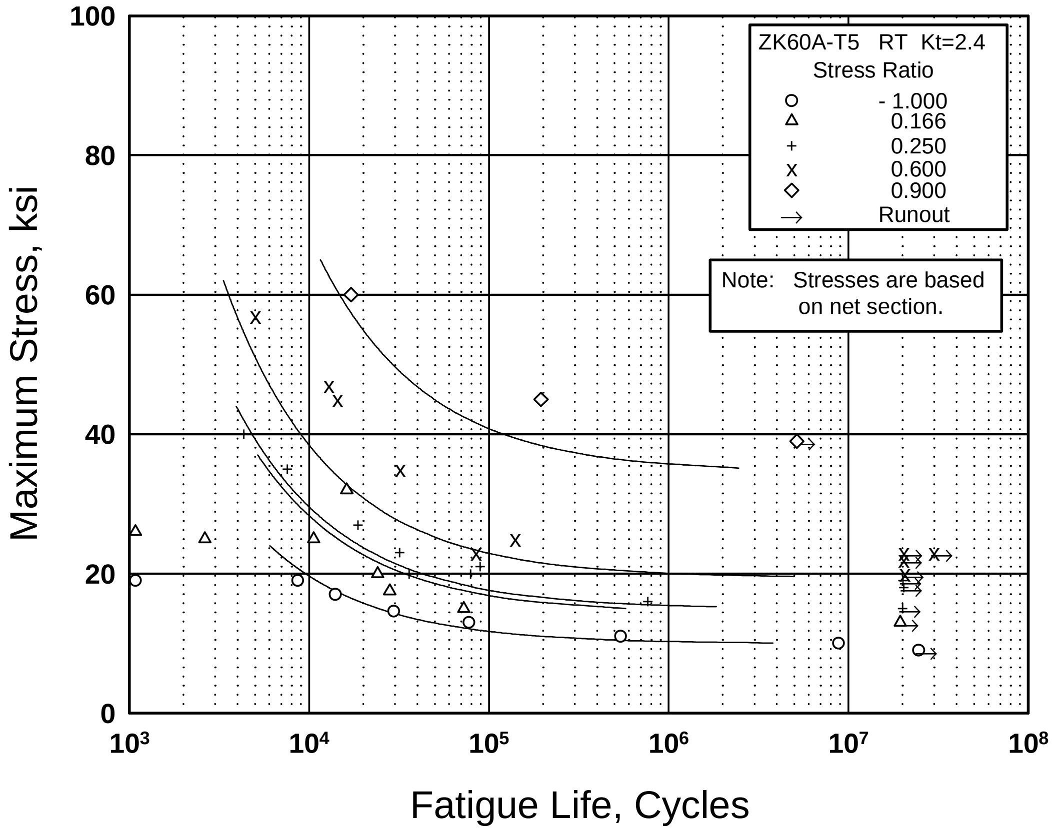

Figure 4.2.3.2.8(b). Best-fit S/N curves for notched, K_t = 2.4, ZK60A-T5 extruded bar, longitudinal direction.

<u>Correlative Information for Figure 4.2.3.2.8(b)</u>

<u>Product Form</u>: Extruded bar, 0.50-inch diameter

<u>Properties</u>:

<u>TUS, ksi</u>	<u>TYS, ksi</u>	<u>Temp.,°F</u>
63.7	40.9	RT (notched)

<u>Specimen Details</u>: Circumferential notched,
K_t = 2.4
0.50-inch gross diameter
0.40-inch net diameter
0.032-inch notch radius
60° flank angle, ω

<u>Surface Condition</u>: Ground with aluminum oxide wheel lubricated with sulfur cutting oil; lapped with a copper rod and No. 600 grit alundum lapping compound

<u>Reference</u>: 4.2.3.2.8

<u>Test Parameters:</u>
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

<u>No. of Heats/Lots</u>: Not specified

<u>Equivalent Stress Equation</u>:
Log N_f = 5.51-1.36 log (S_{eq}-13.2)
$S_{eq} = S_{max}(1-R)^{0.42}$
Std. Error of Estimate, Log (Life) = 0.46
Standard Deviation, Log (Life) = 0.82
R^2 = 69%

<u>Sample Size</u> = 30

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

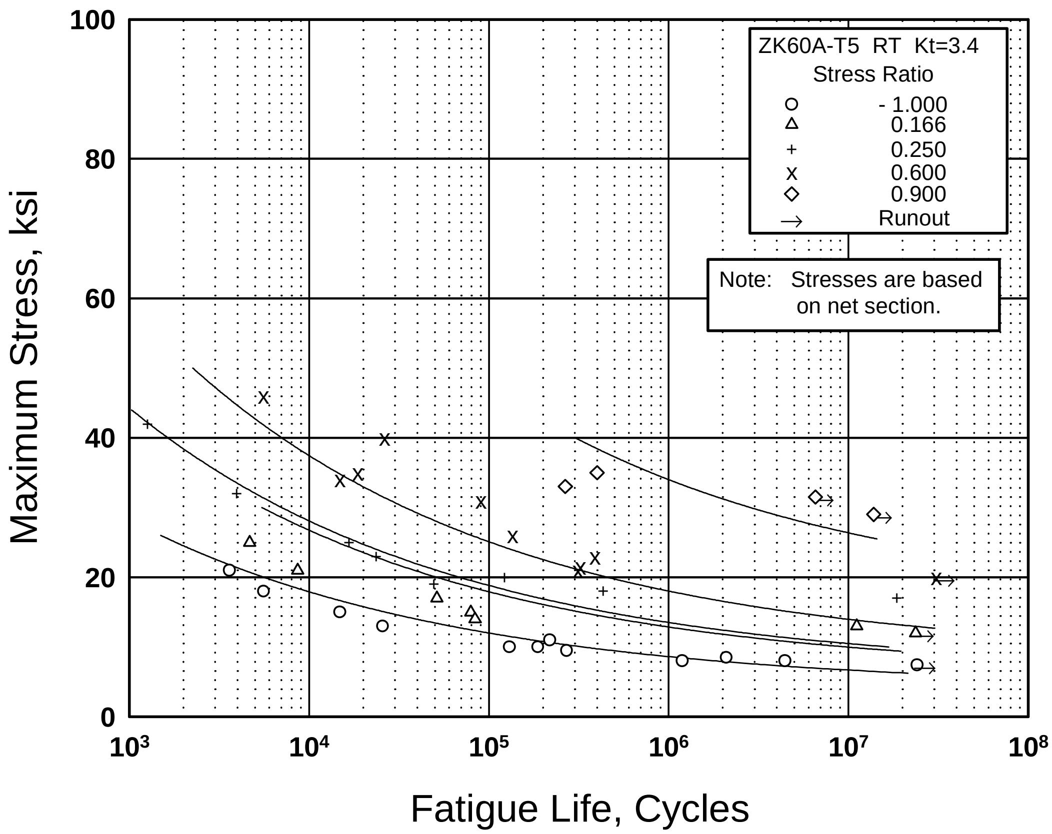

Figure 4.2.3.2.8(c). Best-fit S/N curves for notched, K_t = 3.4, ZK60A-T5 extruded bar, longitudinal direction.

<u>Correlative Information for Figure 4.2.3.2.8(c)</u>

<u>Product Form</u>: Extruded bar, 0.50-inch diameter

<u>Properties</u>:

<u>TUS, ksi</u>	<u>TYS, ksi</u>	<u>Temp., °F</u>
58.2	40.9	RT (notched)

<u>Specimen Details</u>: Circumferential notched,
K_t = 4
0.50-inch gross diameter
0.40-inch net diameter
0.010-inch notch radius
60° flank angle, ω

<u>Surface Condition</u>: Ground with aluminum oxide wheel lubricated with sulfur cutting oil; lapped with a copper rod and No. 600 grit alundum lapping compound

<u>Reference</u>: 4.2.3.2.8

<u>Test Parameters:</u>
Loading - Axial
Frequency - 3600 cpm
Temperature - RT
Environment - Air

<u>No. of Heats/Lots</u>: Not specified

<u>Equivalent Stress Equation</u>:
Log N_f = 9.27-4.13 log (S_{eq}-5.63)
$S_{eq} = S_{max}(1-R)^{0.46}$
Std. Error of Estimate, Log (Life) = 0.55
Standard Deviation, Log (Life) = 0.99
R^2 = 70%

<u>Sample Size</u> = 36

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

4.3 MAGNESIUM CAST ALLOYS

4.3.1 AM100A

4.3.1.0 *Comments and Properties* — AM100A is a magnesium-base casting alloy containing aluminum and a small amount of manganese. It is primarily used as permanent mold castings. AM100A has about the same characteristics as AZ92A. AM100A has less tendency to microshrinkage and hot shortness than the Mg-Al-Zn alloys. It has good weldability and fair pressure tightness.

Material specifications for AM100A are given in Table 4.3.1.0(a). Room-temperature mechanical and physical properties are shown in Table 4.3.1.0(b).

Table 4.3.1.0(a). Material Specifications for AM100A Magnesium Alloy

Specification	Form
AMS 4455	Investment casting
AMS 4483[a]	Permanent mold casting
MIL-M-46062	Casting

a Noncurrent specification.

Table 4.3.1.0(b). Design Mechanical and Physical Properties of AM100A Magnesium Alloy Casting

Specification	AMS 4455	AMS 4483[a]	MIL-M-46062			
Form	Investment casting	Permanent mold casting	Casting (any method)			
Temper	T6	T6	T6			
Location within casting	Any area		Designated area			Nondesignated area
			Class 1[b]	Class 2[b]	Class 3[b]	
Basis	S	S	S	S	S	S
Mechanical Properties[c]:						
F_{tu}, ksi	17[d]	17[d]	38	35	30	17
F_{ty}, ksi	9.5[d]	10[d]	20	18	16	10
F_{cy}, ksi	9.5	10	20	18	16	10
F_{su}, ksi	...	...	...	...	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent	1[c]	...	3	1.5	1	0.75
E, 10^3 ksi	6.5					
E_c, 10^3 ksi	6.5					
G, 10^3 ksi	2.4					
μ	0.35					
Physical Properties:						
ω, lb./in.^{3}	0.0651					
C, K, and α	...					

a Noncurrent specification.
b Class of properties attainable depends on location specified and casting design and should be coordinated with the producer.
c Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.
d When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.

4.3.2 AZ91C/AZ91E

4.3.2.0 *Comments and Properties* — AZ91C is a magnesium-base casting alloy containing aluminum and zinc. AZ91E is a version which contains a significantly lower level of impurities resulting in improved corrosion resistance. These alloys have good castability with a good combination of ductility and strength. AZ91C and AZ91E are the most commonly used sand castings for temperatures under 300°F. AZ91C is available as sand and investment castings, while AZ91E is available as a sand casting. AZ91C and AZ91E have fair weldability and pressure tightness.

Some material specifications covering AZ91C/AZ91E are presented in Table 4.3.2.0(a). Room-temperature mechanical and physical properties are shown in Tables 4.3.2.0(b) and (c).

Table 4.3.2.0(a). Material Specifications for AZ91C/AZ91E Magnesium Alloy

Specification	Form
AMS 4437	Sand casting
AMS 4452	Investment casting
MIL-M-46062	Casting
AMS 4446	Sand casting

The temper index for AZ91C/AZ91E is as follows:

Section	Temper
4.3.2.1	T6

4.3.2.1 *T6 Temper* — Figure 4.3.2.1.4 contains an elevated temperature curve for tension and compression moduli. Typical tensile stress-strain curves at room temperature and several elevated temperatures are presented in Figure 4.3.2.1.6.

Table 4.3.2.0(b). Design Mechanical and Physical Properties of AZ91C Magnesium Alloy Casting

Specification	AMS 4437	AMS 4452	MIL-M-46062			
Form	Sand casting	Investment casting	Casting (any method)			
Temper	T6	T6	T6			
Location within casting	Any area		Designated area			Nondesignated area
			Class 1[a]	Class 2[a]	Class 3[a]	
Basis	S	S	S	S	S	S
Mechanical Properties[b]:						
F_{tu}, ksi	17[c]	17[c]	35	29	27	17
F_{ty}, ksi	12[c]	12[c]	18	16	14	12
F_{cy}, ksi	12	12	18	16	14	12
F_{su}, ksi	...	...	...	...	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent	0.75[c]	1[c]	4	3	2	0.75
E, 10^3 ksi	6.5					
E_c, 10^3 ksi	6.5					
G, 10^3 ksi	2.4					
μ	0.35					
Physical Properties:						
ω, lb./in.^{3}	0.0652					
C, Btu/(lb)(°F)	0.25[d]					
K, Btu/[(hr)(ft^2)(°F)/ft]	41 (212°F to 572°F)					
α, 10^{-6} in./in./°F	14 (65°F to 212°F)					

a Class of properties attainable depends on location specified and casting design and should be coordinated with the producer.
b Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.
c When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.
d Estimated.

4.3.3 AZ92A

4.3.3.0 *Comments and Properties* — AZ92A is a magnesium-base casting alloy containing aluminum and zinc. It is slightly stronger and less ductile than AZ91C but is much like it in other characteristics. It is available as sand and permanent-mold casting. AZ92A has fair weldability and pressure tightness.

Material specifications for AZ92A are presented in Table 4.3.3.0(a). Room-temperature mechanical and physical properties are shown in Table 4.3.3.0(b). Elevated temperature curves for physical properties are shown in Figure 4.3.3.0.

Table 4.3.3.0(a). Material Specifications for AZ92A Magnesium Alloy

Specification	Form
AMS 4434	Sand casting
AMS 4484[a]	Permanent-mold casting
MIL-M-46062	Casting

a Noncurrent specification.

The temper index for AZ92A is as follows:

Section	Temper
4.3.3.1	T6

4.3.3.1 *AZ92A-T6 Temper* — Elevated temperature curves for various mechanical properties are presented in Figures 4.3.3.1.1(a) through (c), and 4.3.3.1.4. Typical stress-strain and tangent-modulus curves at room temperature and several elevated temperatures are shown in Figures 4.3.3.1.6(a) and (b).

Table 4.3.3.0(b). Design Mechanical and Physical Properties of AZ92A Magnesium Alloy Casting

Specification	AMS 4484[a]	AMS 4434	MIL-M-46062			
Form	Permanent mold casting	Sand casting	Casting (any method)			
Temper	T6	T6	T6			
Location within casting	Any area		Designated area			Nondesignated area
			Class 1[b]	Class 2[b]	Class 3[b]	
Basis	S	S	S	S	S	S
Mechanical Properties[c]:						
F_{tu}, ksi	17[d]	17[d]	40	34	30	17
F_{ty}, ksi	13.5[d]	13.5[d]	25	20	18	13
F_{cy}, ksi	13.5	13.5	25	20	18	13
F_{su}, ksi	...	...	...	...	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent	...	...	3	1	0.75	0.50
E, 10^3 ksi	6.5					
E_c, 10^3 ksi	6.5					
G, 10^3 ksi	2.4					
μ	0.35					
Physical Properties:						
ω, lb./in.^{3}	0.0659					
C, Btu/(lb)(°F)	0.25[e]					
K and α	See Figure 4.3.3.0					

a Noncurrent specification.
b Class of properties attainable depends on location specified and casting design and should be coordinated with the producer.
c Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.
d When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.
e Estimated.

Table 4.3.5.0(b). Design Mechanical and Physical Properties of QE22A Magnesium Alloy Casting

Specification	AMS 4418	MIL-M-46062			
Form	Sand casting	Casting (any method)			
Temper	T6				
Location within casting	Any area	Designated area			Nondesignated area
		Class 1[a]	Class 2[a]	Class 3[a]	
Basis	S	S	S	S	S
Mechanical Properties[b]:					
F_{tu}, ksi	32[c]	40	37	33	28
F_{ty}, ksi	23[c]	28	26	23	20
F_{cy}, ksi	23	28	26	23	20
F_{su}, ksi	...	...	...	...	...
F_{bru}, ksi:					
(e/D = 1.5)	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...
F_{bry}, ksi:					
(e/D = 1.5)	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...
e, percent	2[c]	4	2	2	1
E, 10^3 ksi	6.5				
E_c, 10^3 ksi	6.5				
G, 10^3 ksi	2.4				
μ	0.35				
Physical Properties:					
ω, lb/in.^{3}	0.0653				
C, Btu/(lb)(°F)	0.25[d]				
K, Btu/[(hr)(ft^2)(°F)/ft]	59				
α, 10^{-6} in./in./°F	14 (68°F to 392°F)				

a Class of properties attainable depends on location specified and casting design and should be coordinated with the producer.

b Reference should be made to the specific requirements of the procuring or certificating agency with regard to the use of the above values in the design of castings.

c When specified on drawing, conformance to tensile property requirements is determined by testing specimens cut from castings.

d Estimated.

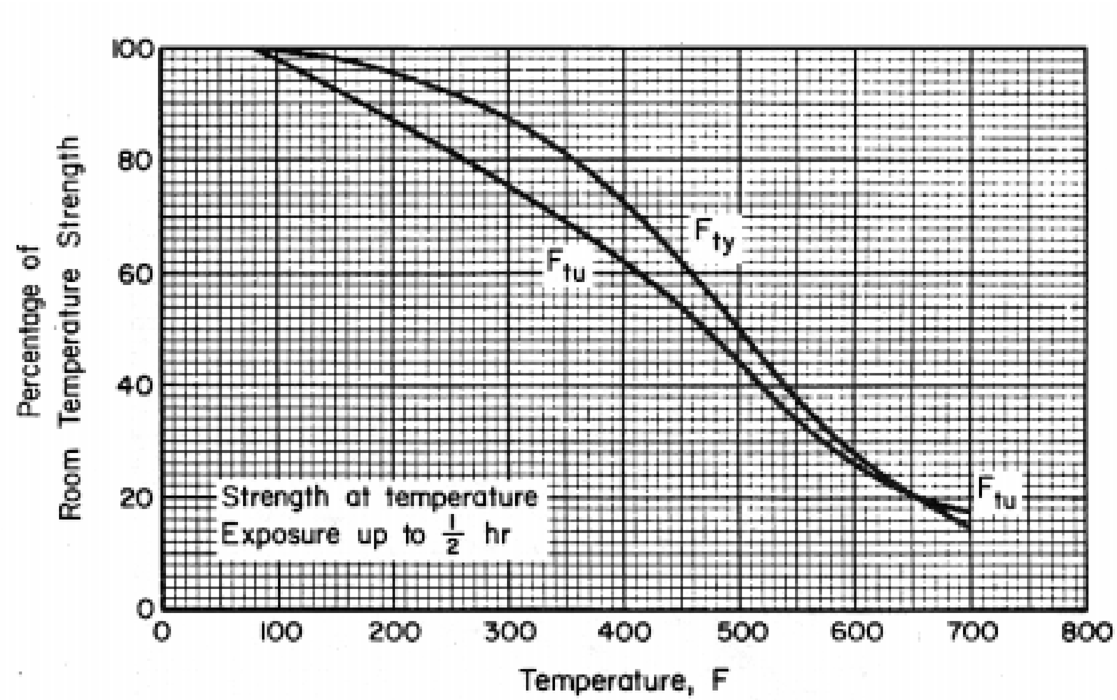

Figure 4.3.5.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of cast QE22A-T6.

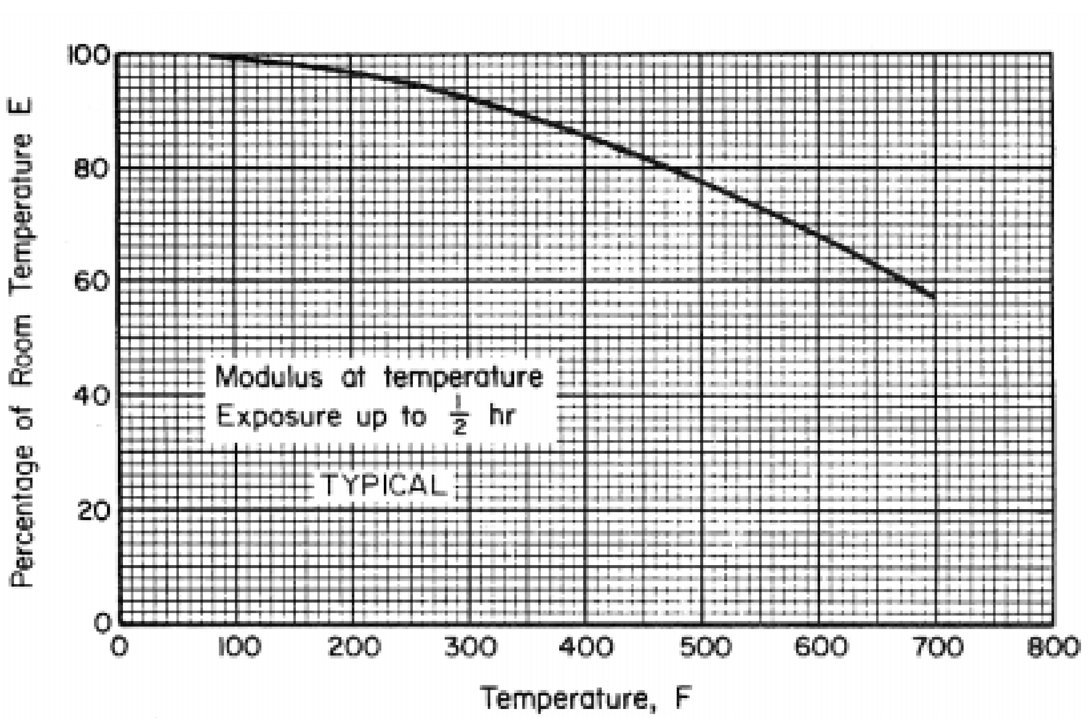

Figure 4.3.5.1.4. Effect of temperature on the tensile modulus (E) of cast QE22A-T6.

CHAPTER 5

TITANIUM

5.1 GENERAL

This chapter contains the engineering properties and related characteristics of titanium and titanium alloys used in aircraft and missile structural applications.

General comments on engineering properties and the considerations relating to alloy selection are presented in Section 5.1. Mechanical- and physical-property data and characteristics pertinent to specific alloy groups or individual alloys are reported in Sections 5.2 through 5.5.

Titanium is a relatively lightweight, corrosion-resistant structural material that can be strengthened greatly through alloying and, in some of its alloys, by heat treatment. Among its advantages for specific applications are: good strength-to-weight ratio, low density, low coefficient of thermal expansion, good corrosion resistance, good oxidation resistance at intermediate temperatures, good toughness, and low heat-treating temperature during hardening, and others.

5.1.1 TITANIUM INDEX — The coverage of titanium and its alloys in this chapter has been divided into four sections for systematic presentation. The system takes into account unalloyed titanium and three groups of alloys based on metallurgical differences which in turn result in differences in fabrication and property characteristics. The sections and the individual alloys covered under each are shown in Table 5.1.

Table 5.1. Titanium Alloys Index

Section	Alloy Designation
5.2	**Unalloyed Titanium**
5.2.1	Commercially Pure Titanium
5.3	**Alpha and Near-Alpha Titanium Alloys**
5.3.1	Ti-5A1-2.5Sn (Alpha)
5.3.2	Ti-8A1-1Mo-1V (Near-Alpha)
5.3.3	Ti-6A1-2Sn-4Zr-2Mo (Near-Alpha)
5.4	**Alpha-Beta Titanium Alloys**
5.4.1	Ti-6A1-4V
5.4.2	Ti-6A1-6V-2Sn
5.4.3	Ti - 4.5Al-3V-2Fe-2Mo
5.5	**Beta, Near-Beta, and Metastable Titanium Alloys**
5.5.1	Ti-13V-11Cr-3A1
5.5.2	Ti-15V-3Cr-3Sn-3A1
5.5.3	Ti-10V-2Fe-3A1

5.1.2 MATERIAL PROPERTIES — The material properties of titanium and its alloys are determined mainly by their alloy content and heat treatment, both of which are influential in determining the allotropic forms in which this material will be bound. Under equilibrium conditions, pure titanium has an "alpha" structure up to 1620°F, above which it transforms to a "beta" structure. The inherent properties of these two structures are quite different. Through alloying and heat treatment, one or the other or a combination of these two structures can be made to exist at service temperatures, and the properties of the material vary accordingly. References 5.1.2(a) and (b) provide general discussion of titanium microstructures and associated metallography.

Titanium and titanium alloys of the alpha and alpha-beta type exhibit crystallographic textures in sheet form in which certain crystallographic planes or directions are closely aligned with the direction of prior working. The presence of textures in these materials lead to anisotropy with respect to many mechanical and physical properties. Poisson's ratio and Young's modulus are among those properties strongly affected by texture. Wide variations experienced in these properties both within and between sheets of titanium alloys have been qualitatively related to variations of texture. In general, the degree of texturing, and hence the variation of Young's modulus and Poisson's ratio, that is developed for alpha-beta alloys tends to be less than that developed in all alpha titanium alloys. Rolling temperature has a pronounced effect on the texturing of titanium alloys which may not in general be affected by subsequent thermal treatments. The degree of applicability of the effect of textural variations discussed above on the mechanical properties of products other than sheet is unknown at present. The values of Young's modulus and Poisson's ratio listed in this document represent the usual values obtained on products resulting from standard mill practices. References 5.1.2(c) and (d) provide further information on texturing in titanium alloys.

5.1.2.1 *Mechanical Properties* —

5.1.2.1.1 *Fracture Toughness* — The fracture toughness of titanium alloys is greatly influenced by such factors as chemistry variations, heat treatment, microstructure, and product thickness, as well as yield strength. For fracture critical applications, these factors should be closely controlled. Typical values of plane-strain fracture toughness for titanium alloys are presented in Table 5.1.2.1.1. Minimum, average, and maximum values, as well as coefficient of variation, are presented for various products for which valid data are available, but these values do not have the statistical reliability of the room-temperature mechanical properties.

5.1.3 MANUFACTURING CONSIDERATIONS — Comments relating to formability, weldability, and final heat treatment are presented under individual alloys. These comments are necessarily brief and are intended only to aid the designer in the selection of an alloy for a specific application. In practice, departures from recommended practices are very common and are based largely on in-plant experience. Springback is nearly always a factor in hot or cold forming.

Final heat treatments that are indicated as "specified" heat treatments do not necessarily coincide with the producers' recommended heat treatments. Rather, these treatments, along with the specified room-temperature minimum tensile properties, are contained in the heat treating-capability requirements of applicable specifications, for example, MIL-H-81200. Departures from the specified aging cycles are often necessary to account for aging that may take place during hot working or hot sizing or to obtain more desirable mechanical properties, for example, improved fracture toughness. More detailed recommendations for specific applications are generally available from the material producers.

5.1.4 ENVIRONMENTAL CONSIDERATIONS — Comments relating to temperature limitations in the application of titanium and titanium alloys are presented under the individual alloys.

Below about 300°F, as well as above about 700°F, creep deformation of titanium alloys can be expected at stresses below the yield strength. Available data indicate that room-temperature creep of unalloyed titanium may be significant (exceed 0.2 percent creep-strain in 1,000 hours) at stresses that exceed approximately 50 percent F_{ty}, room-temperature creep of Ti-5A1-1.5Sn ELI may be significant at stresses above approximately 60 percent F_{ty}, and room-temperature creep of the standard grades of titanium alloys may be significant at stresses above approximately 75 percent F_{ty}. References 5.1.4(a) through (c) provide some limited data regarding room-temperature creep of titanium alloys.

The use of titanium and its alloys in contact with either liquid oxygen or gaseous oxygen at cryogenic temperatures should be avoided, since either the presentation of a fresh surface (such as produced by tensile rupture) or impact may initiate a violent reaction [Reference 5.1.4(d)]. Impact of the surface in contact with liquid oxygen will result in a reaction at energy levels as low as 10 ft-lb. In gaseous oxygen, a partial pressure of about 50 psi is sufficient to ignite a fresh titanium surface over the temperature range from -250°F to room temperature or higher.

Titanium is susceptible to stress-corrosion cracking in certain anhydrous chemicals including methyl alcohol and nitrogen tetroxide. Traces of water tend to inhibit the reaction in either environment. However, in N_2O_4, NO is preferred and inhibited N_2O_4 contains 0.4 to 0.8 percent NO. Red fuming nitric acid with less than 1.5 percent water and 10 to 20 percent NO_2 can crack the metal and result in a pyrophoric reaction.

Titanium alloys are also susceptible to stress corrosion by dry sodium chloride at elevated temperatures. This problem has been observed largely in laboratory tests at 450 to 500°F and higher and occasionally in fabrication shops. However, there have been no reported failures of titanium components in service by hot salt stress corrosion. Cleaning with a nonchlorinated solvent (to remove salt deposits, including fingerprints) of parts used above 450°F is recommended.

In laboratory tests, with a fatigue crack present in the specimen, certain titanium alloys show an increased crack propagation rate in the presence of water or salt water as compared with the rate in air. These alloys also may show reduced sustained load-carrying ability in aqueous environments in the presence of fatigue cracks. Crack growth rates in salt water are a function of sheet or section thickness. These alloys are not susceptible in the form of thin-gauge sheet, but become susceptible as thickness increases. The thickness at which susceptibility occurs varies over a visual range with the alloy and processing. Alloys of titanium found susceptible to this effect include some from alpha, alpha-beta, and beta-type microstructures. In some cases, special processing techniques and heat treatments have been developed that minimize this effect. References 5.1.4(e) through (g) present detailed summaries of corrosion and stress corrosion of titanium alloys.

Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-HDBK-1568 for restrictions concerning applications with titanium in contact with these metals or their compounds.

Table 5.1.2.1.1. Values of Room Temperature Plain-Strain Fracture Toughness of Titanium Alloys[a]

									K_{Ic}, ksi $\sqrt{\text{in.}}$			
Alloy	Heat Treat Condition	Product Form	Orientation[b]	Yield Strength Range, ksi	Product Thickness Range, inches	Number of Sources	Sample Size	Specimen Thickness Range, inches	Max.	Avg.	Min.	Coefficient of Variation
Ti-6Al-4V	Mill Annealed	Forged Bar	L-T	121-143	<3.5	2	43	0.6-1.1	77	60	38	10.5
Ti-6Al-4V	Mill Annealed	Forged Bar	T-L	124-145	<3.5	2	64	0.5-1.3	81	57	33	11.7

a These values are for information only.
b Refer to Figure 1.4.12.3 for definition of symbols.

5.2 UNALLOYED TITANIUM

Several grades of unalloyed titanium are offered and are classified on the basis of manufacturing method, degree of purity, or strength, there being a close relationship among these. The unalloyed titanium grades most commonly used are produced by the Kroll process, are intermediate in purity, and are commonly referred to as being of commercial purity.

5.2.1 COMMERCIALLY PURE TITANIUM

5.2.1.0 *Comments and Properties* — Unalloyed titanium is available in all familiar product forms and is noted for its excellent formability. Unalloyed titanium is readily welded or brazed. It has been used primarily where strength is not the main requirement.

Manufacturing Considerations — Unalloyed titanium is supplied in the annealed condition permitting extensive forming at room temperature. Severe forming operations also can be accomplished at elevated temperatures (300 to 900°F). Property degradation can be experienced after severe forming if as-received material properties are not restored by re-annealing.

Commercially pure titanium can be welded readily by the several methods employed for titanium joining. Atmospheric shielding is preferable although spot or seam welding may be accomplished without shielding. Brazing requires protection from the atmosphere which may be obtained by fluxing as well as by inert gas or vacuum shielding.

Environmental Considerations — Titanium has an unusually high affinity for oxygen, nitrogen, and hydrogen at temperatures above 1050°F. This results in embrittlement of the material, thus usage should be limited to temperatures below that indicated. Additional chemical reactivity between titanium and selected environments such as methyl alcohol, chloride salt solutions, hydrogen, and liquid metal, can take place at lower temperatures, as discussed in Section 5.1.4 and its references.

Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-S-5002 and MIL-STD-1568 for restrictions concerning applications with titanium in contact with these metals or their compounds.

Heat Treatment — Commercially pure titanium is fully annealed by heating to 1000 to 1300°F for 10 to 30 minutes. It is stress relieved by heating to 900 to 1000°F for 30 minutes. Commercially pure titanium cannot be hardened by heat treatment.

Specifications and Properties — Some material specifications for commercially pure titanium are presented in Table 5.2.1.0(a). Room-temperature mechanical properties for commercially pure titanium are shown in Tables 5.1.2.0(b) and (c). The effect of temperature on physical properties is shown in Figure 5.2.1.0.

5.2.1.1 *Annealed Condition* — Elevated-temperature data for annealed commercially pure titanium are presented in Figures 5.2.1.1.1(a) through 5.2.1.1.3(b). Typical full-range stress-strain curves for the 40 and 70 ksi yield strength commercially pure titanium are shown in Figures 5.2.1.1.6(a) and (b).

Table 5.2.1.0(a). Material Specifications for Commercially Pure Titanium

Specification	Form
AMS 4900	Sheet, strip, and plate
AMS 4901	Sheet, strip, and plate
AMS 4902	Sheet, strip, and plate
AMS-T-9046	Sheet, strip, and plate
MIL-T-9047[a]	Bar
AMS 4921	Bar
AMS-T-81556	Extruded bars and shapes

a Inactive for new design

Table 5.2.1.0(b). Design Mechanical and Physical Properties of Commercially Pure Titanium

Specification	MIL-T-9046	AMS 4902 and MIL-T-9046	AMS 4900 and MIL-T-9046	AMS 4901 and MIL-T-9046	AMS 4921 and MIL-T-9047	MIL-T-9047
Designation	CP-4	CP-3	CP-2	CP-1	CP-70	
Form	Sheet, strip, and plate				Bar	
Condition	Annealed				Annealed	
Thickness or diameter, in.	≤ 1.000				≤ 2.999[a]	3.000-4.000[a]
Basis	S	S	S	S	S	S
Mechanical Properties:						
F_{tu}, ksi:						
L	35	50	65	80	80	80
LT	35	50	65	80	80[b]	80
ST	...	...	...	...	...	80
F_{ty}, ksi:						
L	25	40	55	70	70	70
LT	25	40	55	70	70[b]	70
ST	...	...	...	...	...	70
F_{cy}, ksi:						
L	...	...	...	70	...	...
LT	...	...	...	70	...	...
F_{su}, ksi	...	...	...	42	...	...
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	120	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	101	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent:						
L	24[c]	20[c]	18[c]	15[c]	15	15
LT	24[c]	20[c]	18[c]	15[c]	15[b]	15
ST	...	...	...	...	...	15
RA, percent:						
L	...	...	...	...	30	30
LT	...	...	...	...	30[b]	30
ST	...	...	...	...	...	30
E, 10^3 ksi	15.5					
E_c, 10^3 ksi	16.0					
G, 10^3 ksi	6.5					
μ	...					
Physical Properties:						
ω, lb/in.^{3}	0.163					
C, K, and α	See Figure 5.2.1.0					

a Maximum of 16-square-inch cross-sectional area.
b Long transverse properties apply to rectangular bar only for thickness >0.500 inches and widths >3.000 inches. For AMS 4921, (e) (LT) = 12% and RA (LT) = 25%.
c Thickness of 0.025 inch and above.

Table 5.2.1.0(c). Design Mechanical and Physical Properties of Commercially Pure Titanium Extruded Bars and Shapes

Specification	AMS-T-81556			
	Comp. CP-4	Comp. CP-3	Comp. CP-2	Comp. CP-1
Form	Extruded bars and shapes			
Condition	Annealed			
Thickness or diameter, in.	0.188-3.000			
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	40	50	65	80
LT	...	...	...	...
F_{ty}, ksi:				
L	30	40	55	70
LT	...	...	...	...
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
F_{su}, ksi	...	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
e, percent:				
L	a	a	a	a
E, 10^3 ksi	15.5			
E_c, 10^3 ksi	16.0			
G, 10^3 ksi	6.5			
μ	...			
Physical Properties:				
ω, lb/in.^{3}	0.163			
C, K, and α	See Figure 5.2.1.0			

a Elongation in percent as follows:

Thickness, inches	Comp. CP-4	Comp. CP-3	Comp. CP-2	Comp. CP-1
0.188-1.000	25	20	18	15
1.001-2.000	20	18	15	12
2.001-3.000	18	15	12	10

5.3 ALPHA AND NEAR-ALPHA TITANIUM ALLOYS

The alpha titanium alloys contain essentially a single phase at room temperature, similar to that of unalloyed titanium. Alloys identified as near-alpha titanium have principally an all-alpha structure but contain small quantities of a beta phase because the composition contains some beta stabilizing elements. In both alloy types, alpha phase is stabilized by aluminum, tin, and zirconium. These elements, especially aluminum, contribute greatly to strength. The beta stabilizing additions (e.g., molybdenum and vanadium) improve fabricability and metallurgical stability of highly alpha-alloyed materials.

All alpha alloys have excellent weldability, toughness at low temperatures, and long-term elevated-temperature strength. They are well suited to cryogenic applications and to uses requiring good elevated-temperature creep strength. The characteristics of near-alpha alloys are predictably between those of all alpha and alpha-beta alloys in regard to fabricability, weldability, and elevated-temperature strength. The hot workability of both alpha and near-alpha alloys is inferior to that of the alpha-beta or beta alloys and the cold workability is very limited at the high-strength level of these grades. However, considerable forming is possible if correct forming temperatures and procedures are used.

5.3.1 TI-5AL-2.5SN

5.3.1.0 *Comments and Properties* — Ti-5Al-2.5Sn is an all-alpha alloy available in many product forms and at two purity levels. The high purity grade of this composition is used principally for cryogenic applications and may be characterized as having lower strength but higher ductility and toughness than the standard grade. The normal purity grade also may be used at low temperatures but it is primarily suitable for room to elevated temperature applications (up to 900°F or to 1100°F for short times) where weldability is an important consideration.

Manufacturing Considerations — Ti-5Al-2.5Sn is not so readily formed into complex shapes as other alloys with similar room-temperature properties, but far surpasses them in weldability. Except for some forging operations, fabrication of Ti-5Al-2.5Sn is conducted at temperatures where the structure remains all alpha. Severe forming operations may be accomplished at temperatures up to 1200°F. Moderately severe forming can be done at 300 to 600°F and simple forming may be done at room temperature. Most forming and welding operations are followed by an annealing treatment to relieve residual stresses imposed by the prior operation.

Ti-5Al-2.5Sn can be welded readily by inert-gas or vacuum-shielded arc methods or by spot or seam welding without atmospheric shielding. Brazing requires protection from the atmosphere; however, this is accomplished by fluxing as well as by inert gas or vacuum shielding.

Environmental Considerations — Ti-5Al-2.5Sn is metallurgically stable at moderate elevated temperatures. The material is susceptible to hot-salt stress corrosion as well as aqueous chloride solution stress corrosion. Care should be exercised in applications involving such environments. The alloy has good oxidation resistance up to 1050°F. Standard grade material has been used at moderately low cryogenic temperatures; however, the ELI grade has higher toughness and has been used in cryogenic applications down to -423°F. Under certain conditions, titanium, when in contact with cadmium, silver, mercury, or certain of their compounds, may become embrittled. Refer to MIL-HDBK-1568 for restrictions concerning applications with titanium in contact with these metals or their compounds.

Heat Treatment — This alloy is annealed by heating 1400°F for 60 minutes and 1600°F for 10 minutes and cooling in air. Stress relieving requires 1 or 2 hours at 1000 to 1200°F. Ti-5Al-2.5Sn cannot be hardened by heat treatment.

Specifications and Properties — Some material specifications for Ti-5Al-2.5Sn are shown in Table 5.3.1.0(a). Room-temperature mechanical properties for Ti-5Al-2.5Sn are shown in Tables 5.3.1.0(b) through (d). The effect of temperature on physical properties is shown in Figure 5.3.1.0.

Table 5.3.1.0(a). Material Specifications for Ti-5Al-2.5Sn

Specification	Form
AMS-T-9046	Sheet, strip, and plate
AMS 4926	Bar
MIL-T-9047[a]	Bar
AMS-T-81556	Extruded bar and shapes
AMS 4910	Sheet, strip, and plate
AMS 4966	Forging

a Inactive for new design

5.3.1.1 ***Annealed Condition*** — Elevated temperature curves for annealed Ti-5Al-2.5Sn are shown in Figures 5.3.1.1.1 through 5.3.1.1.5. Tensile properties cover the range -423°F to 1000°F; whereas other properties are for the range room temperature to 1000°F. Fatigue-crack-propagation data for sheet are shown in Figures 5.3.1.1.9(a) through (c).

Table 5.3.1.0(b). Design Mechanical and Physical Properties of Ti-5Al-2.5Sn Sheet, Strip, and Plate

Specification	AMS 4910 and AMS-T-9046, Comp. A-1								
Form	Strip	Sheet				Plate			
Condition	Annealed								
Thickness, in.	<0.187	0.015-0.079		0.080-0.187		0.188-0.250		0.251-1.500	1.501-4.000
Basis	S	A	B	A	B	A	B	S	S
Mechanical Properties:									
F_{tu}, ksi:									
L	120	120[a]	128	120[a]	131	120[a]	135	120	115
LT	120	120[a]	129	120[a]	132	120[a]	137	120	115
F_{ty}, ksi:									
L	113	110	115	113	118	113[a]	123	113	110
LT	113	113	118	113[a]	121	113[a]	125	113	110
F_{cy}, ksi:									
L	115	115	120	118	123	118	128	118	...
LT	118	118	123	118	126	118	130	118	...
F_{su}, ksi	75	75	80	75	82	75	85	75	...
F_{bru}, ksi:									
(e/D = 1.5)	167	167	179	167	183	167	190	167	...
(e/D = 2.0)	250	250	268	250	275	250	285	250	...
F_{bry}, ksi:									
(e/D = 1.5)	133	133	139	133	142	133	147	133	...
(e/D = 2.0)	190	190	198	190	203	190	210	190	...
e, percent (S-basis):									
L	10	10[b]	...	10	...	10	...	10	10
LT	10	10[b]	...	10	...	10	...	10	10
E, 10^3 ksi	15.5								
E_c, 10^3 ksi	15.5								
G, 10^3 ksi	...								
μ	...								
Physical Properties:									
ω, lb/in.^{3}	0.162								
C, K, and α	See Figure 5.3.1.0								

a S-basis. The rounded T_{99} values are higher than specification values as follows:

	0.015-0.079	0.080-0.187	0.188-0.250
F_{tu}			
L......	123	126	130
LT......	123	126	131
F_{ty}			
L.......	....	...	118
LT......	....	115	120

b Thickness 0.025 inch and above.

Table 5.3.1.0(c). Design Mechanical and Physical Properties of Ti-5Al-2.5Sn Bar and Forging

Specification	AMS 4926[a] and MIL-T-9047[b]			AMS 4966
Form	Bar			Forging
Condition	Annealed			Annealed
Thickness or diameter, in.	≤2.999[c]		3.000-4.000[c]	...
Basis	A	B	S	
Mechanical Properties:				
F_{tu}, ksi:				
L	115[d]	126	115	115
LT	115[e]	...	115	115[f]
ST	...	...	115	115[f]
F_{ty}, ksi:				
L	110[d]	120	110	110
LT	110[e]	...	110	110[f]
ST	...	...	110	110[f]
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
F_{su}, ksi	...	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
e, percent (S-basis):				
L	10	...	10	10
LT	10[e]	...	10	10[f]
ST	...	...	8	10[f]
RA, percent (S-basis):				
L	25	...	25	25
LT	25[e]	...	25	25[f]
ST	...	...	20	25[f]
E, 10^3 ksi	15.5			
E_c, 10^3 ksi	15.5			
G, 10^3 ksi	...			
μ	...			
Physical Properties:				
ω, lb/in.^{3}	0.162			
C, K, and α	See Figure 5.3.1.0			

a For AMS 4926, LT and ST values for *e* and *RA* may be different than those shown.
b Inactive for new design.
c Maximum of 16-square-inch cross-sectional area.
d The rounded T_{99} values are higher than S values as follows: F_{tu} = 117 ksi, F_{ty} = 113 ksi.
e S-basis. Applicable providing LT dimension is >3.000 inches.
f Applicable, providing LT or ST dimension is ≥2.500 inches.

Table 5.3.1.0(d). Design Mechanical and Physical Properties of Ti-5Al-2.5Sn Extrusion

Specification	AMS-T-81556, Comp. A-1			
Form	Extruded bars and shapes			
Condition	Annealed			
Thickness or diameter, in.	0.188-1.000	1.001-2.000	2.001-3.000	3.001-4.000
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	120	115	115	115
LT	...	...	...	...
F_{ty}, ksi:				
L	115	110	110	110
LT	...	...	...	...
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
F_{su}, ksi	...	...	...	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)				
(e/D = 2.0)				
e, percent:				
L	10	10	8	6
LT	...	...	...	...
E, 10^3 ksi	15.5			
E_c, 10^3 ksi	15.5			
G, 10^3 ksi	...			
μ	...			
Physical Properties:				
ω, lb/in.^{3}	0.162			
C, K, and α	See Figure 5.3.1.0			

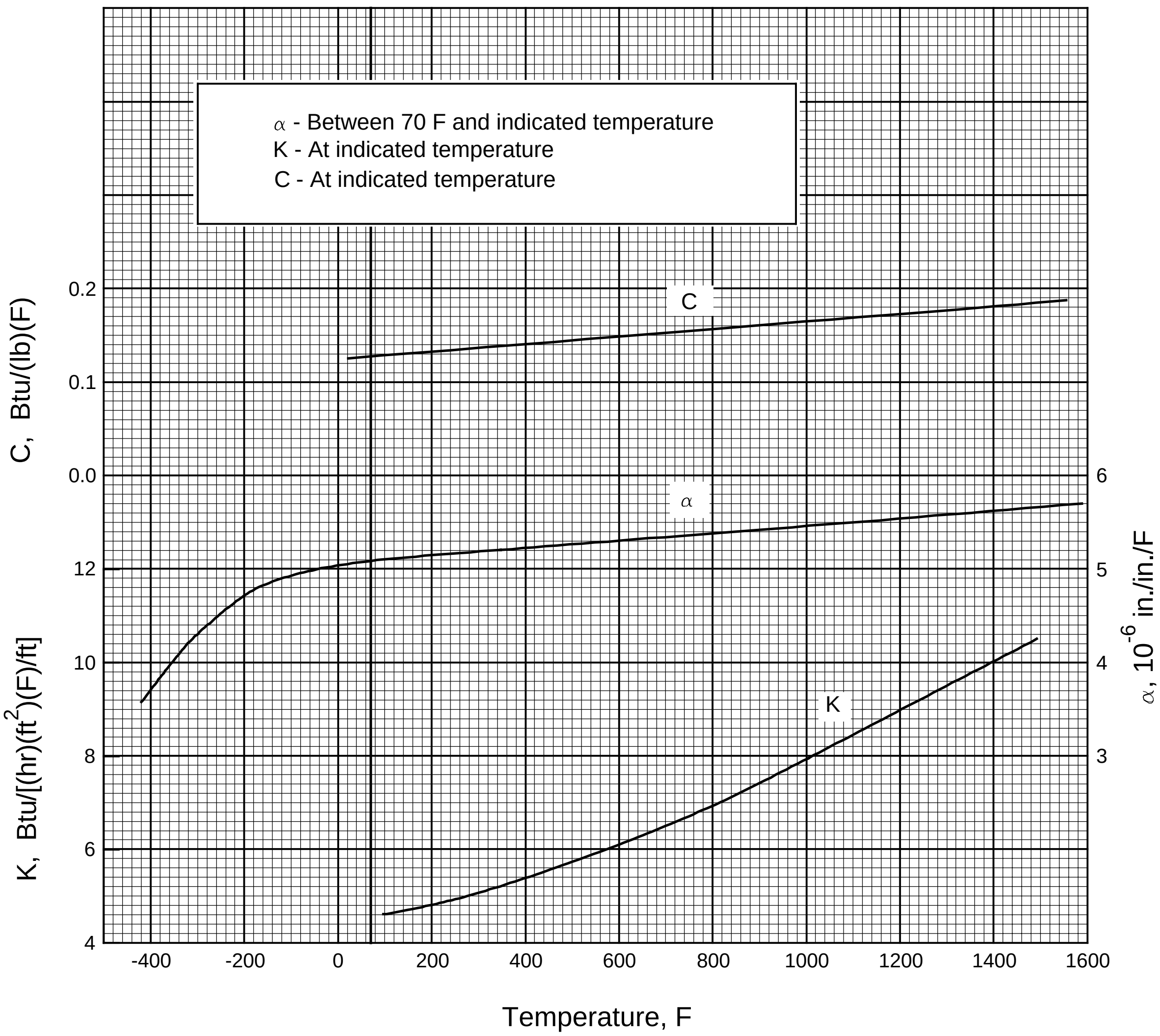

Figure 5.3.1.0. Effect of temperature on the physical properties of Ti-5Al-2.5Sn alloy.

Table 5.3.3.0(b). Design Mechanical and Physical Properties of Ti-6Al-2Sn-4Zr-2Mo

Specification	AMS 4919								AMS-T-9046, Comp. AB-4
Form	Sheet								
Condition	Duplex annealed								Triplex annealed
Thickness or diameter, in.	≤0.046		0.047-0.093		0.094-0.140		0.141-0.187		≤0.187
Basis	A	B	A	B	A	B	A	B	S[a]
Mechanical Properties:									
F_{tu}, ksi:									
L	135[b]	143	135[b]	143	135[b]	143	135[b]	143	145
LT	135[b]	143	135[b]	143	135[b]	143	135[b]	143	145
F_{ty}, ksi:									
L	125[c]	136	125[c]	136	125[c]	136	125[c]	136	135
LT	125[c]	134	125[c]	134	125[c]	134	125[c]	134	135
F_{cy}, ksi:									
L	132	142	132	142	132	142	132	142	...
LT	132	142	132	142	132	142	132	142	...
F_{su}, ksi	...	...	...	...	...	...	...	...	...
F_{bru}[d], ksi:									
(e/D=1.5)	195	206	205	217	214	227	219	232	...
(e/D=2.0)	217	230	243	258	266	282	279	295	...
F_{bry}[d], ksi:									
(e/D=1.5)	171	183	171	183	171	183	171	183	...
(e/D=2.0)	202	217	202	217	202	217	202	217	...
e, percent (S-basis):									
L	8[e]	...	e	...	10	...	10	...	e
LT	8[e]	...	e	...	10	...	10	...	e
E, 10^3 ksi	16.5								
E_c, 10^3 ksi	18.0								
G, 10^3 ksi	6.2								
μ	0.32								
Physical Properties:									
ω, lb/in.^{3}	0.164								
C, K and α	See Figure 5.3.3.0								

a S-basis values are representative of test specimens excised from duplex annealed material and thermally treated to triplex annealed condition in a laboratory furnace.
b S-basis. The rounded T_{99} values are as follows: F_{tu}(L&LT) = 139 ksi.
c S-basis. The rounded T_{99} values are as follows: F_{ty}(L) = 131 ksi and F_{ty}(LT) = 129 ksi.
d Bearing values are "dry pin" values per Section 1.4.7.1.
e 8% for 0.025 through 0.062 inch and 10% for >0.062 inch.

Table 5.3.3.0(c). Design Mechanical and Physical Properties of Ti-6Al-2Sn-4Zr-2Mo

Specification	AMS 4975		AMS 4976
Form	Bar		Forging
Condition	STA (Duplex annealed)		STA (Duplex annealed)
Cross-Sectional area, in.^{2}	≤16		≤9
Thickness, or diameter, in.	≤3.000		≤3.000
Basis	A	B	S
Mechanical Properties:			
F_{tu}, ksi:			
L	130[a]	144	130
LT	130[b]	...	130[b]
ST	130[b]	...	130[b]
F_{ty}, ksi:			
L	120[a]	131	120
LT	120[b]	...	120[b]
ST	120[b]	...	120[b]
F_{cy}, ksi:			
L	...	...	...
LT	...	...	...
ST	...	...	...
F_{su}, ksi	...	...	...
F_{bru}, ksi:			
(e/D=1.5)	...	...	...
(e/D=2.0)	...	...	...
F_{bry}, ksi:			
(e/D=1.5)	...	...	...
(e/D=2.0)	...	...	...
e, percent(S basis):			
L	10	...	10
LT	10[b]	...	10[b]
ST	10[b]	...	10[b]
RA, percent (S basis):			
L	25	...	25
LT	25[b]	...	25[b]
ST	25[b]	...	25[b]
E, 10^3 ksi	16.5		
E_c, 10^3 ksi	18.0		
G, 10^3 ksi	6.2		
μ	0.32		
Physical Properties:			
ω, lb/in.^{3}	0.164		
C, K, and α	See Figure 5.3.3.0		

a S basis. The rounded T_{99} values are as follows: F_{tu}(L) = 138 ksi and F_{ty}(L) = 125 ksi.
b S basis. Applicable providing transverse dimension is ≥2.500 in.

Table 5.4.1.0(e). Design Mechanical and Physical Properties of Ti-6Al-4V Extrusion

Specification	AMS 4935				AMS 4934							
Form	Extrusion											
Condition	Annealed				Solution treated and aged							
Thickness or diameter, in.	≤2.000		2.001-3.000		<0.500		0.501-0.750		0.751-1.000		1.001-2.000	2.001-3.000
Basis	A	B	A	B	A	B	A	B	A	B	S	S
Mechanical Properties:												
F_{tu}, ksi:												
L	130[a]	137	130[b]	135	155	163	151	157	147	153	140	130
LT[c]	130[a]	139	130[b]	139	155	163	151	157	147	155	140	130
F_{ty}, ksi:												
L	120	124	118	122	138	147	138	143	133	140	130	120
LT[c]	120[a]	128	120	125	138	147	138	145	133	142	130	120
F_{cy}, ksi:												
L	128	133	124	128	147	157	147	153	142	150	139	128
LT[c]	129	138	...	...	147	157	147	155	139	152	139	128
F_{su}, ksi	83	89	...	...	94	99	92	96	89	93	85	79
F_{bru}[d], ksi:												
(e/D = 1.5)	214	226	...	...	243	256	237	246	231	240	220	204
(e/D = 2.0)	264	278	...	...	311	327	303	315	295	307	281	261
F_{bry}[d], ksi:												
(e/D = 1.5)	180	186	...	...	208	222	208	216	201	212	196	182
(e/D = 2.0)	210	217	...	...	242	257	242	250	233	245	228	210
e, percent (S-basis):												
L	10	...	10	...	6	...	6	...	6	...	6	6
LT[c]	8	...	8	...	6	...	6	...	6	...	6	6
RA, percent (S-basis):												
L	20	...	20	...	12	...	12	...	12	...	12	12
LT[c]	15	...	15	...	12	...	12	...	12	...	12	12
E, 10^3 ksi	16.9											
E_c, 10^3 ksi	17.2											
G, 10^3 ksi	6.2											
μ	0.31											
Physical Properties:												
ω, lb/in.^{3}	0.160											
C, K, and α	See Figure 5.4.1.0											

a S-basis. The rounded T_{99} values are higher than specification values as follows: F_{tu} (L) and (LT) = 132 ksi and F_{ty} (LT) = 121 ksi.
b S-basis. The rounded T_{99} values are higher than specification values as follows: F_{tu} (L) = 132 ksi and F_{tu} (LT) = 136 ksi.
c Applicable, providing LT dimension is ≥2.500 inches.
d Bearing values are "dry pin" values per Section 1.4.7.1.

Table 5.4.1.0(f). Design Mechanical and Physical Properties of Ti-6Al-4V Die Forging

Specification	AMS 4928			AMS 4920	
Form	Die forging				
Condition	Alpha-beta processed, annealed			Alpha-beta or beta processed, annealed	
Thickness, in.	≤2.000	2.001-4.000	4.001-6.000	≤2.000	2.001-6.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	135	130	130	130	130
LT	135[a]	130[a]	130	130[a]	130[a]
ST	...	130[a]	130	...	130[a]
F_{ty}, ksi:					
L	125	120	120	120	120
LT	125[a]	120[a]	120	120[a]	120[a]
ST	...	120[a]	120	...	120[a]
F_{cy}, ksi:					
L	...	123	123	...	123
LT	...	128	128	...	128
ST	...	...	...	...	...
F_{su}, ksi	...	79	79	...	79
F_{bru}, ksi:					
(e/D = 1.5)	...	203	203	...	203
(e/D = 2.0)	...	257	257	...	257
F_{bry}, ksi:					
(e/D = 1.5)	...	171	171	...	171
(e/D = 2.0)	...	201	201	...	201
e, percent:					
L	10	10	10	8	8
LT	10[a]	10[a]	10	8[a]	8[a]
ST	...	10[a]	8	...	8[a]
RA, percent:					
L	25	25	20	15	15
LT	20[a]	20[a]	20	15[a]	15[a]
ST	...	15[a]	15	...	15[a]
E, 10^3 ksi	16.9				
E_c, 10^3 ksi	17.2				
G, 10^3 ksi	6.2				
μ	0.31				
Physical Properties:					
ω, lb/in.^{3}	0.160				
C, K, and α	See Figure 5.4.1.0				

a Applicable providing LT or ST dimension is ≥2.500 inches.

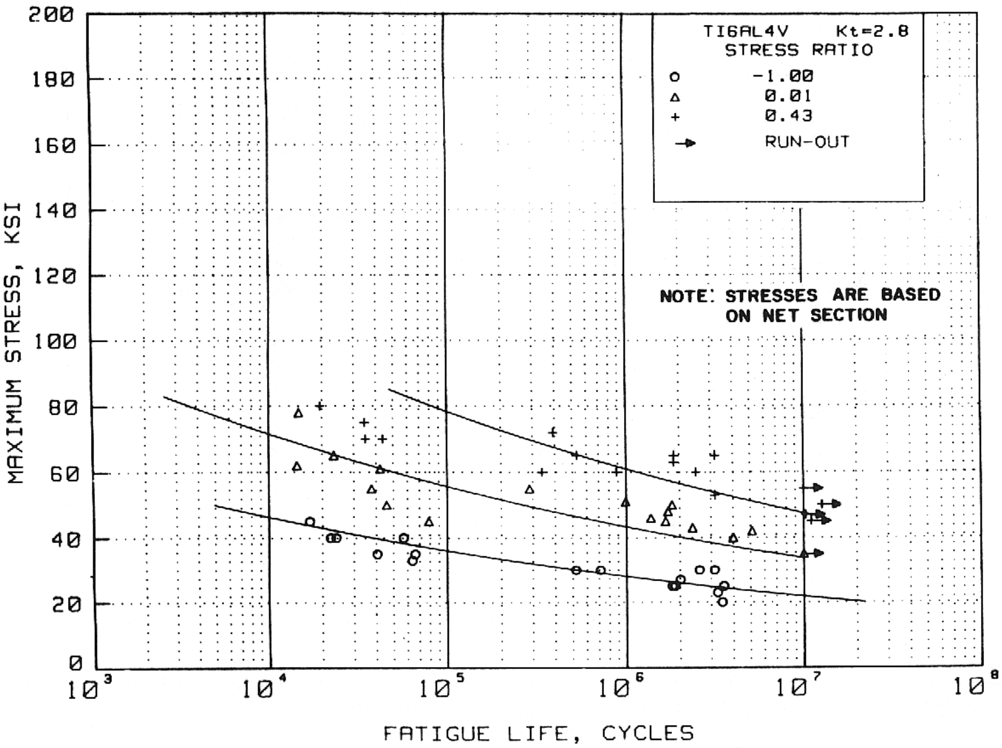

Figure 5.4.1.1.8(e). Best-fit S/N curves for notched, K_t = 2.8, annealed Ti-6Al-4V extrusion at 400 and 600EF, longitudinal direction.

Correlative Information for Figure 5.4.1.1.8(e)

Product Form: Extrusion, 0.300- and 0.560-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp.,EF
112	92	400
101	77	600

Specimen Details: Notched, hole type, K_t = 2.8
0.250-inch hole diameter
1.250-inch net width
1.500-inch gross width

Surface Conditions: RMS 63

Reference: 5.4.1.1.8(b)

Test Parameters:
Loading — Axial
Frequency — 1800 cpm
Temperature — 400EF and 600EF
Environment — Air

No. of Heats/Lots: Not specified

Equivalent Strain Equation:

Log N_f = 21.0-9.18 log (S_{eq})
$S_{eq} = S_{max}(1\text{-}R)^{0.62}$
Std. Error of Estimate, Log (Life) = 0.50
Standard Deviation, Log (Life) = 0.89
R^2 = 68%

Sample Size = 47

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

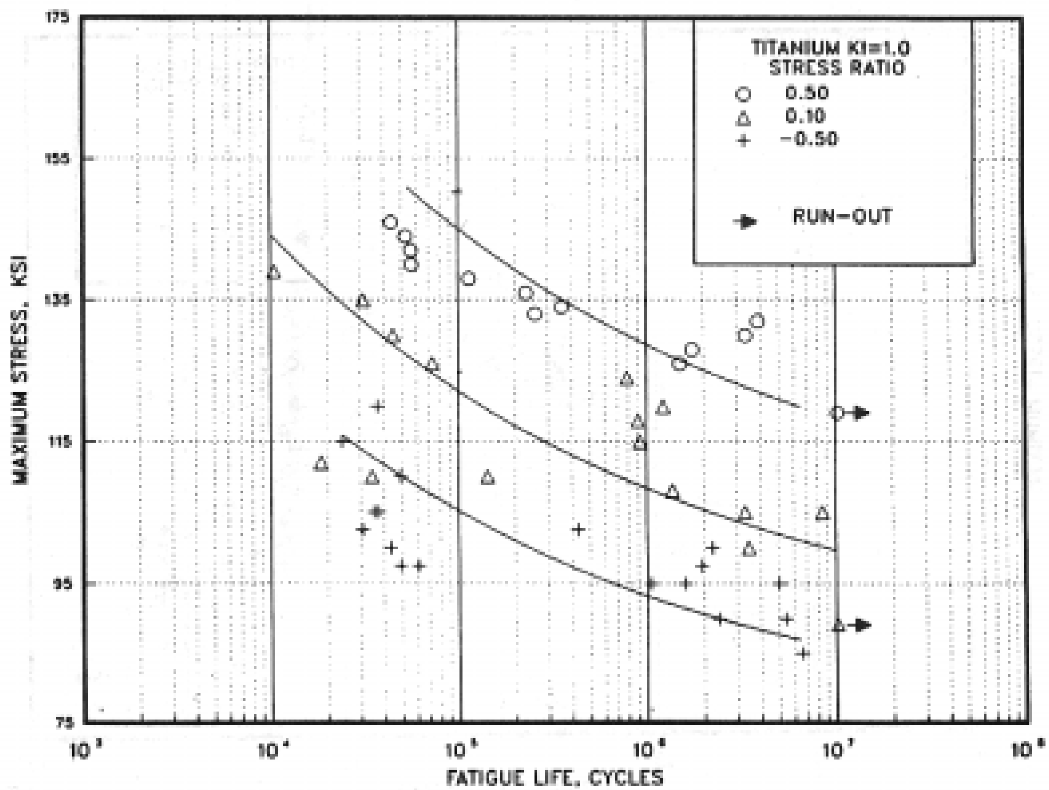

Figure 5.4.1.1.8(f). Best-fit S/N curves for unnotched Ti-6Al-4V annealed sheet, long transverse direction.

Correlative Information for Figure 5.4.1.1.8(f)

Product Form: Sheet, 0.063, 0.070, 0.078-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	147-152	136-143	RT

Specimen Details: Unnotched, 0.375-inch width

Surface Conditions: Machined to 32 RMS, lightly polished with 400 grit emery paper

Reference: 5.4.1.1.8(c)

Test Parameters:

Loading — Axial
Frequency — 10-95 Hz
Temperature — RT
Environment — Air

No. of Heats/Lots: 3

Equivalent Strain Equation:

Log N_f = 12.59-4.89 log (S_{eq}-82.8)
$S_{eq} = S_{max}(1\text{-}R)^{0.29}$
Standard Deviation of Log Life = 0.62
Adjusted R^2 = 50.6%

Sample Size: 47

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

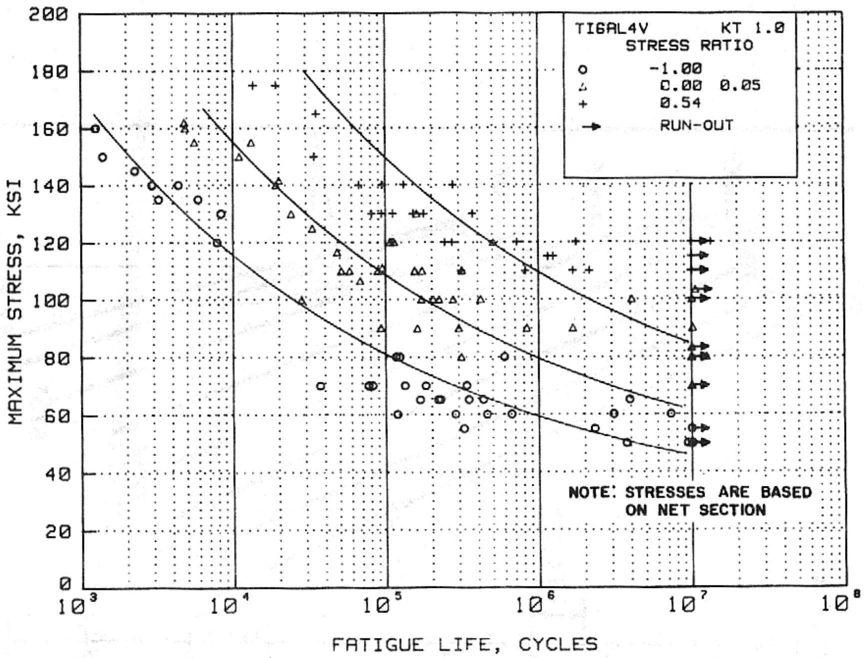

Figure 5.4.1.2.8(a). Best-fit S/N curves for unnotched solution-treated and aged Ti-6Al-4V sheet at room temperature, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(a)

Product Forms: Sheet, 0.063-inch and 0.125-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,EF
	166-177	153-167	RT

Specimen Details: Unnotched
Ref. 5.4.3.2.8(a)
Specimen details not available
Ref. 5.4.3.2.8(b)
1.000-inch net width
8.000-inch test section radius
3.00-inch gross width

Surface Conditions:
Ref. 5.4.3.2.8(a). Edges finished with a crocus cloth.
Ref. 5.4.3.2.8(b). Machined specimens were cleaned with methyl ethyl ketone. Edges polished with number 1 and 00 grit emery paper, recleaned with methyl ethyl ketone.

References: 5.4.1.2.8(a) and (b)

Test Parameters:
Loading — Axial
Frequency —
Ref. 5.4.3.2.8(a), not specified
Ref. 5.4.3.2.8(b), 1500-2200 cpm
Temperature — RT
Environment — Air

No. of Heats/Lots: 4

Equivalent Strain Equation:

Log N_f = 14.29-4.91 log (S_{eq}-30.6)
$S_{eq} = S_{max}(1\text{-}R)^{0.42}$
Std. Error of Estimate, Log (Life) = 0.48
Standard Deviation, Log (Life) = 0.90
R^2 = 72%

Sample Size: 99

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

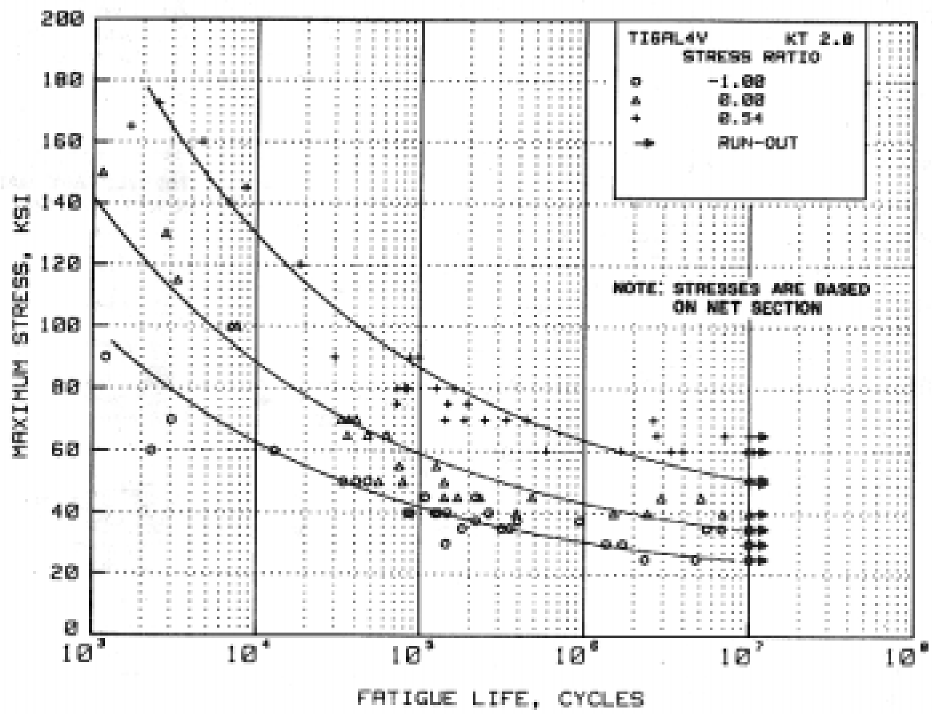

Figure 5.4.1.2.8(b). Best-fit S/N curves for notched, K_t = 2.8, solution-treated and aged Ti-6Al-4V sheet at room temperature, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(b)

Product Forms: Sheet, 0.063-inch and 0.125-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp., °F
166-177	153-167	RT

Specimen Details: Notched, hole type, K_t = 2.8
0.9375-inch net width
1.000-inch gross width
8.000-inch test section radius
0.0625-inch-diameter hole

Surface Conditions: Machined specimens were cleaned with methyl ethyl ketone. Edges polished with number 1 and 00 grit emery paper and recleaned with methyl ethyl ketone.

Reference: 5.4.1.2.8(b)

Test Parameters:
Loading — Axial
Frequency — 1500-2200 cpm
Temperature — RT
Environment — Air

No. of Heats/Lots: 3

Equivalent Strain Equation:

$\text{Log } N_f = 10.87\text{-}3.80 \log (S_{eq}\text{-}24.0)$
$S_{eq} = S_{max}(1\text{-}R)^{0.50}$
Standard Error of Estimate = 0.43
Standard Deviation in Life = 0.98
R^2 = 81%

Sample Size: 87

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

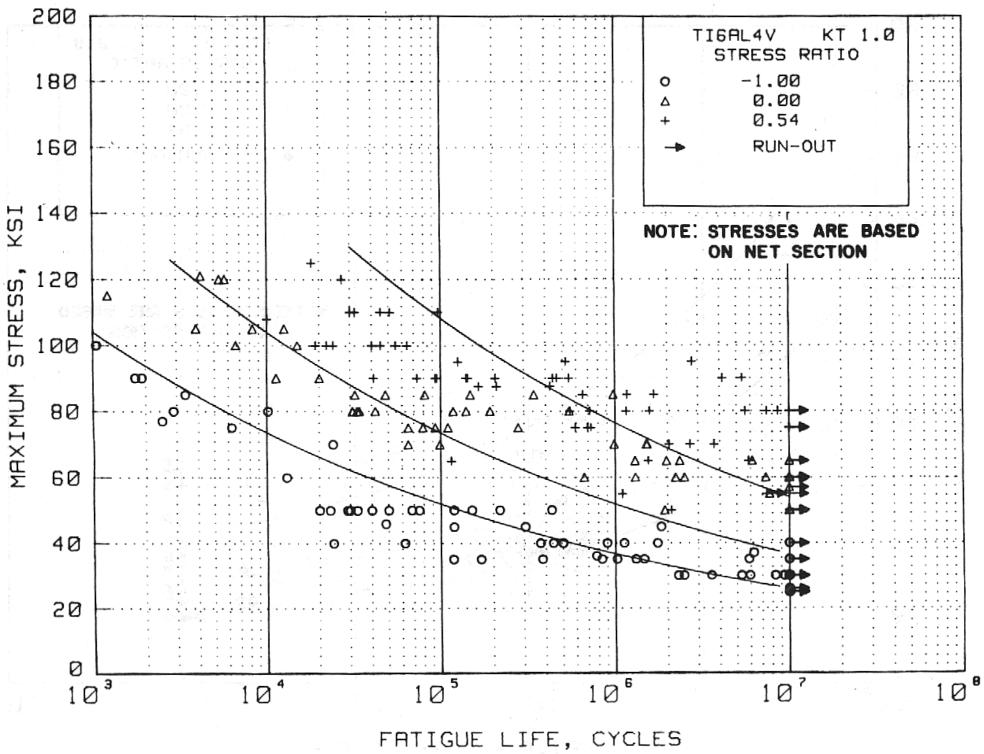

Figure 5.4.1.2.8(e). Best-fit S/N curves for unnotched solution-treated and aged Ti-6Al-4V sheet at 800EF and 900EF, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(e)

Product Forms: Sheet, 0.063-inch and 0.125-inch thick

Properties:

TUS, ksi	TYS, ksi	Temp.,EF
120-125	93-96	800EF
110-111	84-86	900EF

Specimen Details: Unnotched
1.000-inch gross width
8.000-inch test section radius
3.00-inch gross width
0.9375-inch net width

Surface Conditions: Machined specimens were cleaned with methyl ethyl ketone. Edges polished with number 1 and 00 grit emery paper and recleaned with methyl ethyl ketone.

References: 5.4.1.2.8(b)

Test Parameters:
Loading — Axial
Frequency — 1500-2200 cpm
Temperature — 800EF and 900EF
Environment — Air

No. of Heats/Lots: 3

Equivalent Stress Equation:

Log N_f = 17.34-6.61 log (S_{eq})
$S_{eq} = S_{max}(1-R)^{0.50}$
Std. Error of Estimate, Log (Life) = 0.51
Standard Deviation, Log (Life) = 0.99
R^2 = 73%

Sample Size: 154

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

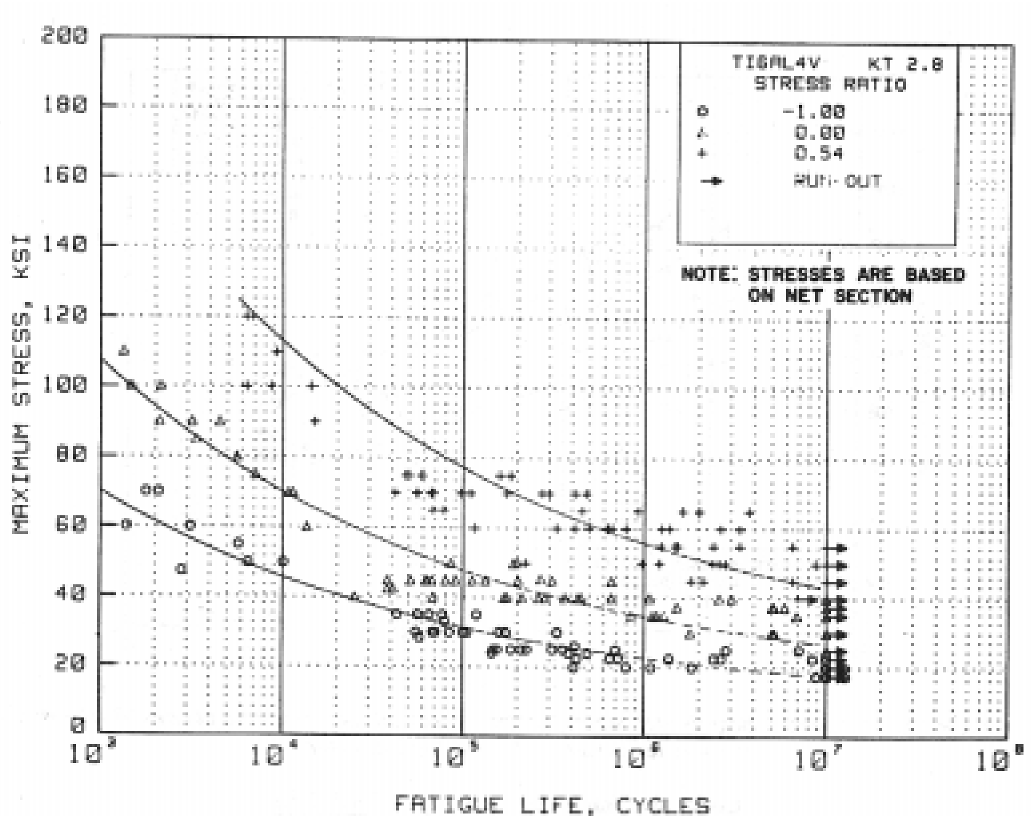

Figure 5.4.1.2.8(f). Best-fit S/N curves for notched, K_t = 2.8, solution-treated and aged Ti-6Al-4V sheet at 800°F and 900°F, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(f)

Product Forms: Sheet, 0.063-inch and 0.125-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,°F
	120-124	93-96	800°F
	110-111	84-88	900°F

Specimen Details: Notched, hole type, K_t = 2.8
1.000-inch gross width
8.000-inch test section radius
0.0625-inch-diameter hole
0.9375-inch net width

Surface Conditions: Machined specimens were cleaned with methyl ethyl ketone. Edges polished with number 1 and 00 grit emery paper and recleaned with methyl ethyl ketone.

Reference: 5.4.1.2.8(b)

Test Parameters:
Loading — Axial
Frequency — 1500-2200 cpm
Temperature — 800°F and 900°F
Environment — Air

No. of Heats/Lots: 3

Equivalent Stress Equation:

Log N_f = 11.75-4.45 log (S_{eq}-15.0)
$S_{eq} = S_{max}(1-R)^{0.62}$
Standard Error of Estimate = 0.43
Standard Deviation in Life = 0.96
R^2 = 79%

Sample Size: 173

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

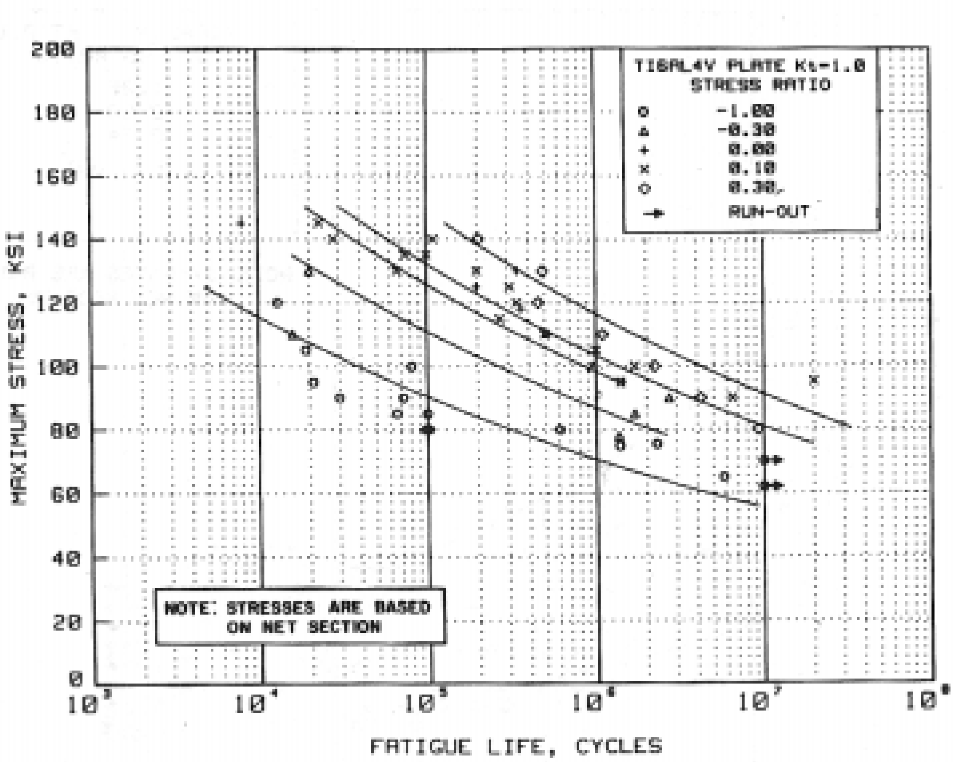

Figure 5.4.1.2.8(g). Best-fit S/N curves for unnotched solution-treated and aged Ti-6Al-4V plate at room temperature, longitudinal direction.

Correlative Information for Figure 5.4.1.2.8(g)

Product Form: Plate, 1.00-inch

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	158	149	RT
	155	145	RT

Specimen Details: Unnotched, rounded

Uniform Gage	Hourglass	
---	3.25	Reduced section radius of curvature, inch
0.195	0.250	Diameter, inch

Surface Condition: Longitudinally polished with No. 000 emery paper removing all circumferential marks.

References: 5.4.1.2.8(c) and (d)

Test Parameters:
Loading — Axial
Frequency — 1,800-18,000 cpm
Temperature — RT
Environment — Air

No. of Heats/Lots: 2

Equivalent Stress Equation:

$\text{Log } N_f = 24.6 - 9.35 \log (S_{eq})$
$S_{eq} = S_{max}(1-R)^{0.48}$
Standard Error of Estimate = 0.39
Standard Deviation in Life = 0.83
$R^2 = 79\%$

Sample Size: 49

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

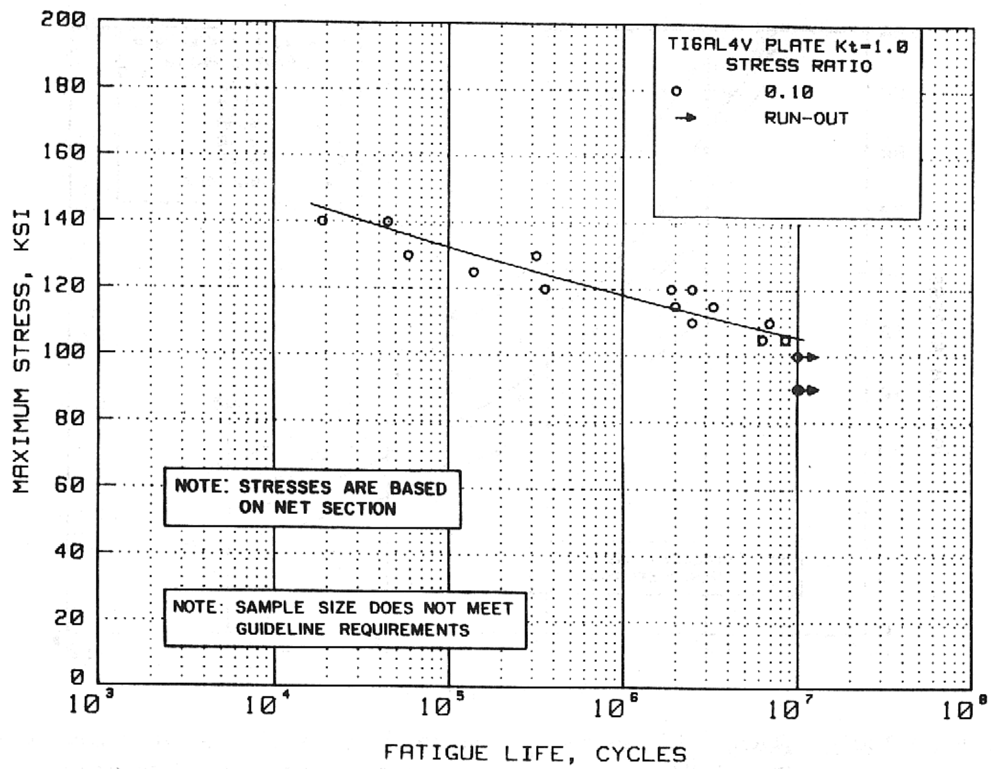

Figure 5.4.1.2.8(h). Best-fit S/N curves for unnotched solution-treated and aged Ti-6Al-4V plate at room temperature, long transverse direction.

Correlative Information for Figure 5.4.1.2.8(h)

Product Form: Plate, 0.50-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp.,EF
	173	164	RT

Specimen Details: Unnotched, flat hourglass
10-inch reduced section radius of curvature
1-inch net section width
0.156-inch net section thickness

Surface Conditions: Machined to 63 RMS

Reference: 5.4.1.2.8(d)

Test Parameters:
Loading — Axial
Frequency — Unspecified
Temperature — RT
Environment — Air

No. of Heats/Lots: 1

Maximum Stress Equation:

$\log N_f = 47.9 - 20.2 \log (S_{max})$
Std. Error of Estimate, Log (Life) = 0.33
Standard Deviation, Log (Life) = 0.89
$R^2 = 87\%$

Sample Size: 14

Table 5.4.2.0(a). Material Specifications for Ti-6Al-6V-2Sn

Specification	Form
AMS-T-9046	Sheet, strip, and plate
AMS 4979	Bar and forging
AMS-T-81556	Extruded bar and shapes
AMS 4971	Bar and forging
AMS 4978	Bar and forging
AMS 4918	Sheet, strip, and plate

Table 5.4.2.0(b). Design Mechanical and Physical Properties of Ti-6AI-6V-2Sn Sheet, Strip, and Plate

Specification	AMS -T-9046, Comp. AB-3, and AMS 4918							AMS-T-9046, Comp. AB-3			
Form	Sheet, strip, and plate										
Condition	Annealed							Solution treated and aged			
Thickness, in.	<0.1875		0.1875-0.500	0.501-1.000	1.001-1.500	1.501-2.000	2.001-4.000	≤0.1875	0.1875-1.500	1.501-2.500	2.501-4.000
Basis	A	B	S	S	S	S	S	S	S	S	S
Mechanical Properties:											
F_{tu}, ksi:											
L	155	160	150	150	150	150	145	170	170	160	150
LT	155	150	150	150	150	150	145	170	170	160	150
F_{ty}, ksi:											
L	145[a]	152	140	140	140	140	135	160	160	150	140
LT	145[a]	154	140	140	140	140	135	160	160	150	140
F_{cy}, ksi:											
L	...	...	139	142	146	148	...	...	170	...	...
LT	...	...	151	147	141	136	...	...	170	...	...
F_{su}, ksi	...	...	91	93	95	95	...	...	101	...	...
F_{bru}, ksi:											
(e/D = 1.5)	...	...	236	241	247	250	...	...	264	...	...
(e/D = 2.0)	...	...	294	303	312	317	...	...	324	...	...
F_{bry}, ksi:											
(e/D = 1.5)	...	...	193	196	199	202	...	...	237	...	...
(e/D = 2.0)	...	...	215	223	234	240	...	...	266	...	...
e, percent (S-basis):											
L	10[b]	...	10	10	10	10	8	8	8	6	6
LT	8[b]	...	8	8	8	8	6	6	8	6	6
E, 10^3 ksi	16.0										
E_c, 10^3 ksi	16.4										
G, 10^3 ksi	6.2										
μ	0.31										
Physical Properties:											
ω, lb/in.^{3}	0.164										
C, K, and α	See Figure 5.4.2.0										

a The rounded T_{99} values are higher than specification values as follows: F_{ty} (L) = 147 ksi, F_{ty} (LT) = 149 ksi.

b Longitudinal <0.025 in. = 8 percent. Long transverse < 0.025 in. = 6 percent.

Table 5.4.2.0(e). Design Mechanical and Physical Properties of Ti-6Al-6V-2Sn Extruded Bar and Shapes

Specification	AMS-T-81556, Comp. AB-3							
Form	Extruded bar and shapes							
Condition	Annealed				Solution treated and aged			
Thickness or diameter, in.	≤2.000		2.001-3.000	3.001-4.000	0.188-0.500	0.501-1.500	1.501-2.500	2.501-4.000
Basis	A	B	S	S	S	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								
L	142	148	145	140	170	165	160	150
LT	141	148	145	140	170	165	160	150
F_{ty}, ksi:								
L	129	135	135	130	160	155	150	140
LT	128	135	135	130	160	155	150	140
F_{cy}, ksi:								
L	137	144	140	135	165	160	155	145
LT	136	142	140	135	165	160	155	145
F_{su}, ksi	93	97	...	...	...	...	...	...
F_{bru}[a], ksi:								
(e/D=1.5)	218	229	...	...	...	...	...	...
(e/D=2.0)	268	281	...	...	...	...	...	...
F_{bry}[a], ksi:								
(e/D=1.5)	196	203	...	...	...	...	...	...
(e/D=2.0)	227	235	...	...	...	...	...	...
e, percent (S-basis):								
L	10	...	10	10	8	8	8	8
LT	8	...	8	8	6	6	6	6
RA, percent (S-basis):								
L	20	...	20	20	15	15	15	15
LT	15	...	15	15	12	12	12	12
E, 10^3 ksi	16.0							
E_c, 10^3 ksi	16.4							
G, 10^3 ksi	6.2							
μ	0.31							
Physical Properties:								
ω, lb/in.^{3}	0.164							
C, K, and α	See Figure 5.4.2.0							

a Bearing values are "dry pin" values per Section 1.4.7.1.

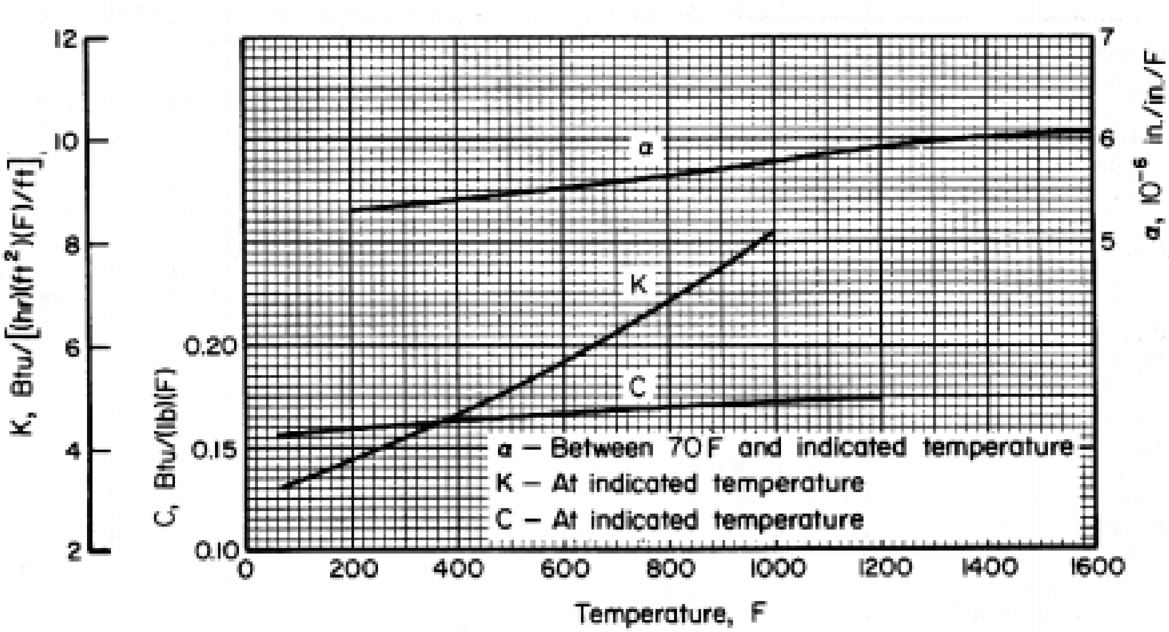

Figure 5.4.2.0. Effect of temperature on the physical properties of Ti-6Al-6V-2Sn alloy.

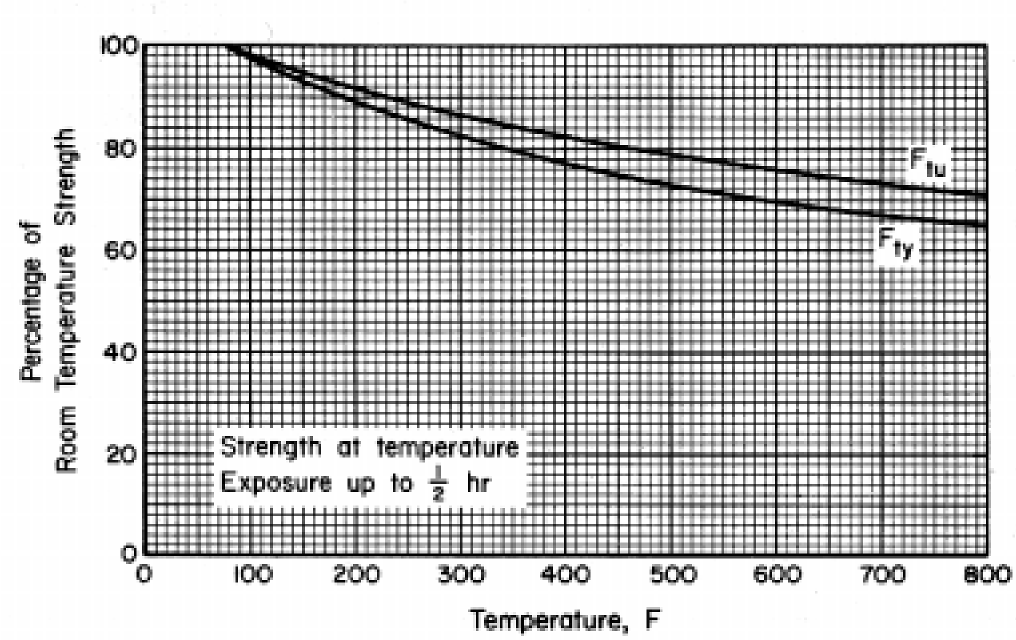

Figure 5.4.2.2.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of solution-treated and aged Ti-6Al-6V-2Sn plate.

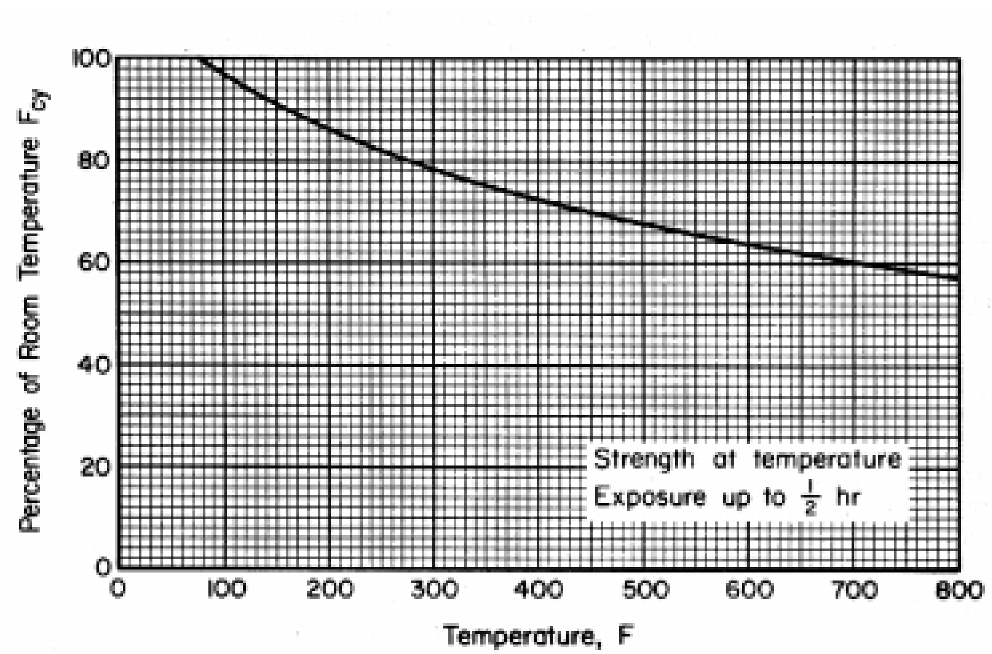

Figure 5.4.2.2.2. Effect of temperature on compressive yield strength (F_{cy}) of solution-treated and aged Ti-6Al-6V-2Sn plate.

5.4.3 Ti-4.5Al-3V-2Fe-2Mo

5.4.3.0 Comments and Properties —Ti-4.5Al-3V-2Fe-2Mo alloy is a beta rich alpha-beta titanium composition developed for improved hot formability and fatigue resistance. The alloy consists of fine microstructure and has excellent superplastic formability at temperatures below 1475°F. This alloy also shows significantly improved cold formability over Ti-6Al-4V. Although this alloy was originally developed for flat product applications in the annealed condition, it has expanded into other areas such as billets, bars, and forgings. This alloy has been reported to possess significantly better hardenability than Ti-6Al-4V.

Manufacturing Considerations – Superplastic forming of Ti-4.5Al-3V-2Fe-2Mo at temperatures between 1380F-1425°F is recommended. At these forming temperatures the formation of alpha case is not observed and the thickness of oxygen enriched layer is generally less than 1/1000”. Diffusion bonding at 1425°F is possible but slightly higher temperatures than the superplastic forming temperature e.g., 1470°F are recommended to ensure perfect bonding. Ti-4.5Al-3V-2Fe-2Mo is weldable by standard titanium welding techniques. This alloy shows an increase in hardness in the welded zone but with limited ductility loss. Stress relief annealing after welding is recommended.

Environmental Considerations – Ti-4.5Al-3V-2Fe-2Mo exhibits significantly improved resistance to aqueous chloride solution stress-corrosion cracking over Ti-6Al-4V. The alloy is nearly equivalent to Ti-6Al-4V hot - salt stress corrosion cracking.

Heat Treatment – This alloy is commonly specified in the annealed condition, but is also used in the solution-treated and aged condition.

Annealing : 1325°F for a time commensurate with product thickness.

Annealing requires 1 hour at 1475°F followed by furnace cooling if maximum ductility is required.
The solution treated and aged conditions commonly employed are as follows :
Solution treat at 1500-1580°F for 1/2 –1hour followed by air cooling.
Age at 900-1060°F followed by air cooling.

Specifications and Properties – Some material specifications for Ti-4.5Al-3V-2Fe-2Mo are shown in Table 5.4.3.0(a). Room temperature mechanical properties and physical properties are shown in Table 5.4.3.0(b).

Table 5.4.3.0(a). Material Specification for Ti-4.5 Al-3V-2Fe-2Mo Titanium Alloy

Specification	Form
AMS 4899	Sheet, Strip, and Plate

5.4.3.1 Anneal Condition – Typical tensile stress-strain and full-range stress-strain curves are shown in Figures 5.4.3.1.6(a) and (b). Compressive stress-strain and tangent modulus curves are shown in Figure 5.4.3.1.6(c). Unnotched and notched fatigue data as well as fatigue crack propagation data are presented in Figures 5.4.3.1.8(a), (b) and 5.4.3.1.9.

Table 5.4.3.0 (b). Design Mechanical and Physical Properties of Ti-4.5 Al-3V-2Fe-2Mo Titanium Alloy Sheet

Specification	AMS 4899			
Form	Sheet			
Condition	Annealed			
Thickness, in.	0.025 to 0.063, exclusive		0.063 to 0.187, exclusive	
Basis	A	B	A	B
Mechanical Properties:				
F_{tu}, ksi:				
L	134[a]	145	134[a]	144
LT	134[a]	147	134[a]	144
F_{ty}, ksi:				
L	126[a]	134	126[a]	132
LT	126[a]	137	126[a]	134
F_{cy}, ksi:				
L	128[a]	136	...	...
LT	131[a]	143	...	...
F_{su},[b] ksi	90[a]	99	...	...
F_{bru},[c] ksi:				
(e/D = 1.5)	196[a]	215	...	...
(e/D = 2.0)	258[a]	283	...	...
F_{bry},[c] ksi:				
(e/D = 1.5)	157[a]	171	...	...
(e/D = 2.0)	190[a]	207	...	...
e, percent (S-basis):				
L	8	...	10	...
LT	8	...	10	...
E, 10^3 ksi	16.0			
E_c, 10^3 ksi	16.2			
G, 10^3 ksi	...			
μ	...			
Physical Properties:				
ω, lb/in.^{3}	0.164			
C, Btu/(lb)(°F)	0.12			
K, Btu/[(hr)(ft^2)(°F)/ft]	4.00			
α, 10^{-6} in./in./°F	5.17 (60-932 °F)			

a Rounded T_{99} values are shown in Table 5.4.3.0(c).
b Determined in accordance with ASTM B769.
c Bearing values are "dry pin" values per Section 1.4.7.1.

Table 5.4.3.0(c).Rounded T_{99} Values for Ti-4.5 Al-3V-2Fe-2Mo Titanium Alloy Sheet

Thickness, in.	0.025 to 0.063, exclusive	0.063 to 0.187, exclusive
Mechanical Properties:		
F_{tu}, ksi:		
L	140	141
LT	140	140
F_{ty}, ksi:		
L	129	128
LT	131	127
F_{cy}, ksi:		
L	131	...
LT	136	...
F_{su},[a] ksi	94	...
F_{bru},[b] ksi:		
(e/D = 1.5)	205	...
(e/D = 2.0)	270	...
F_{bry},[b] ksi:		
(e/D = 1.5)	164	...
(e/D = 2.0)	198	...

a Determined in accordance with ASTM B769.
b Bearing values are “dry pin” values per Section 1.4.7.1.

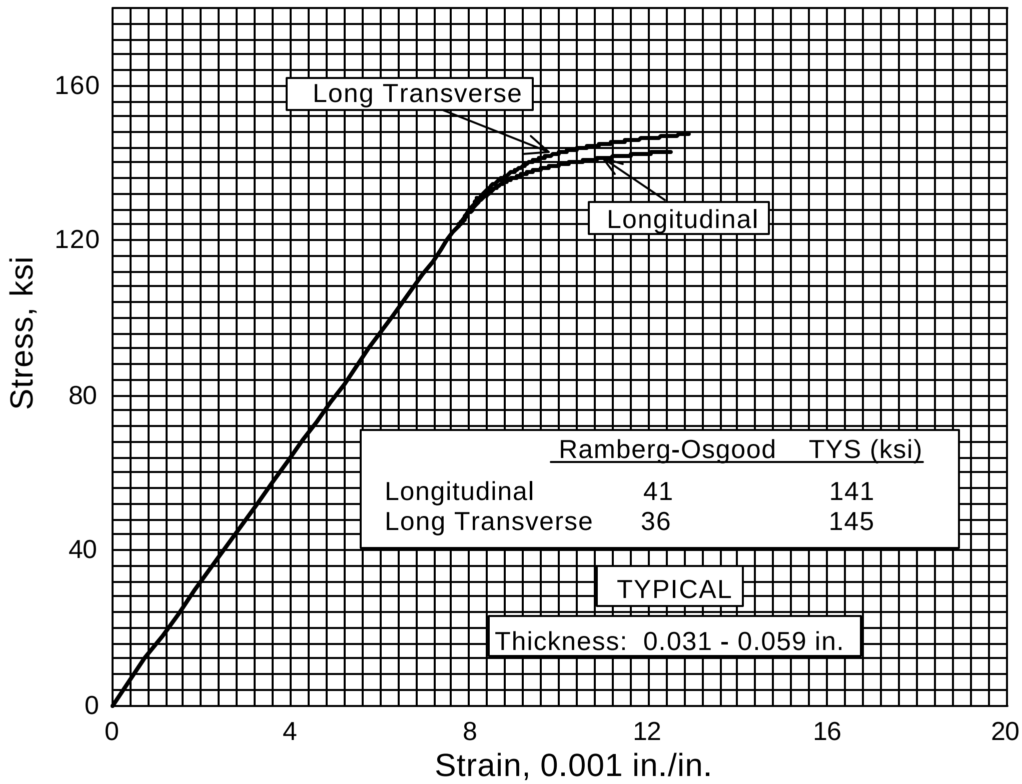

Figure 5.4.3.1.6(a). Typical tensile stress-strain curves at room temperature for annealed Ti-4.5Al-3V-2Fe-2Mo alloy sheet.

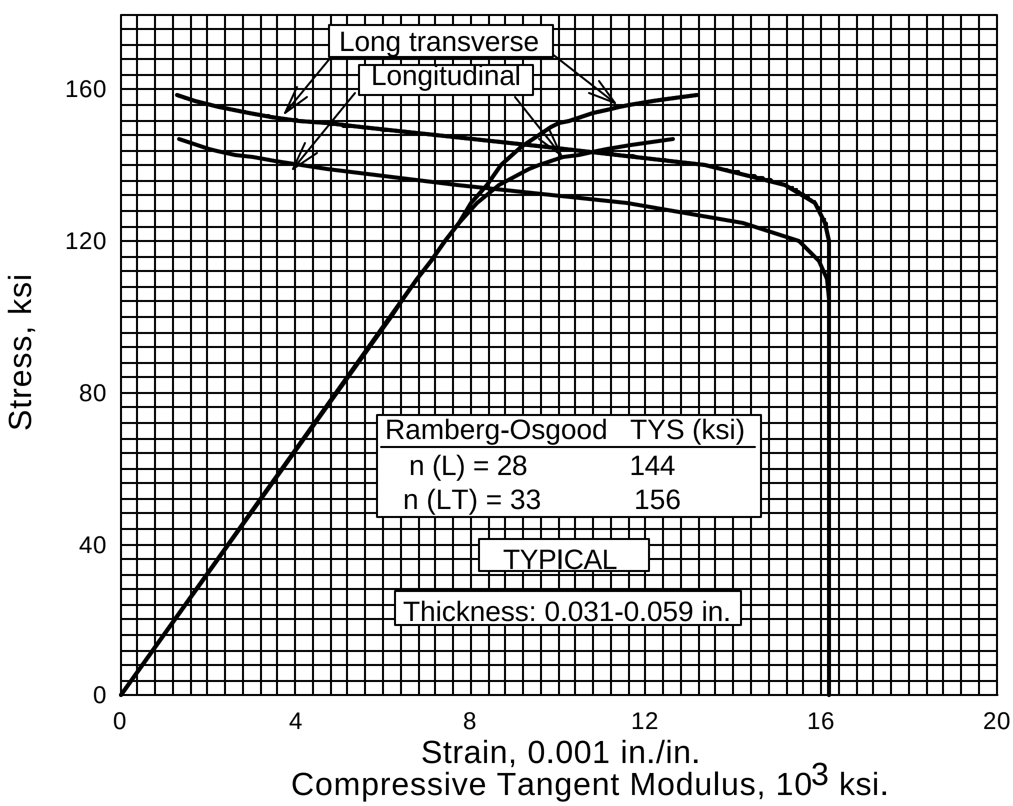

Figure 5.4.3.1.6(b). Typical compressive stress-strain and tangent-modulus curves at room temperature for annealed Ti-4.5Al-3V-2Fe-2Mo alloy sheet.

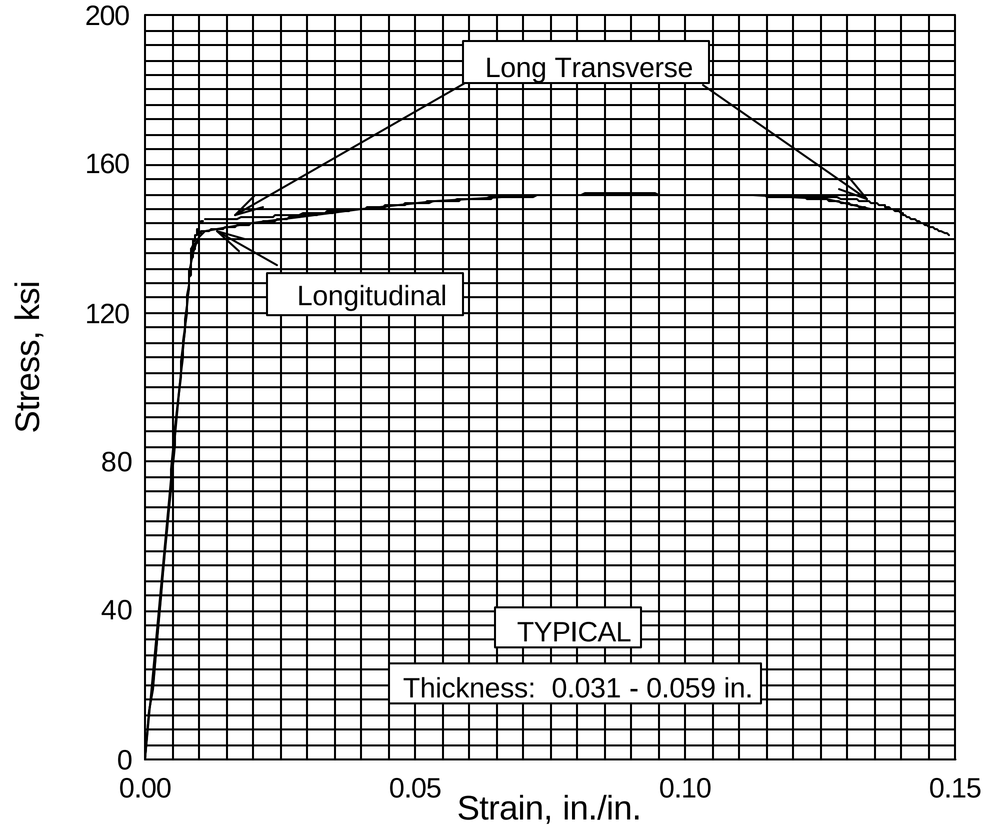

Figure 5.4.3.1.6(c). Typical tensile stress-strain curves (full-range) for annealed Ti-4.5Al-3V-2Fe-2Mo alloy sheet.

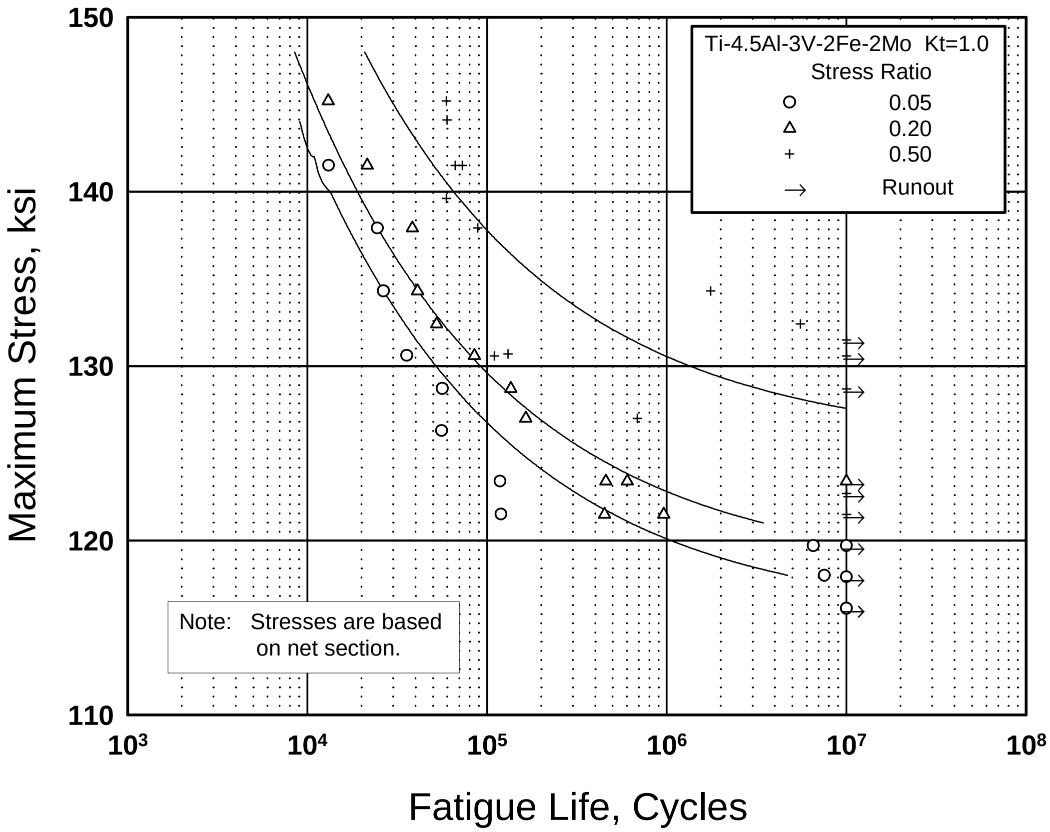

Figure 5.4.3.1.8 (a) Best-fit S/N curves for unnotched Ti-4.5Al-3V-2Fe-2Mo annealed sheet.

Correlative Information for Figure 5.4.3.1.8 (a)

Product Form: 0.059, 0.118, 0.157-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	148 - 149	135 - 138	RT

Specimen Details: Unnotched, 0.252-inch width

Surface Conditions: Lightly polished with 400 grit emery paper

References: 5.4.3.1.8

Test Parameter:
Loading - Axial
Frequency - 10Hz
Temperature - RT
Environment - Air

No. of Heats : 3

Equivalent Stress Equation:
$\text{Log } N_f = 7.72 - 2.59 \log (S_{eq} - 114.68)$
$S_{eq} = S_{max} (1 - R)^{0.13}$
Std. Error of Estimate, Log (Life) = 0.40
Standard Deviation, Log (Life) = 0.60
Adjusted R^2 = 56.5%

Sample Size : 43

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

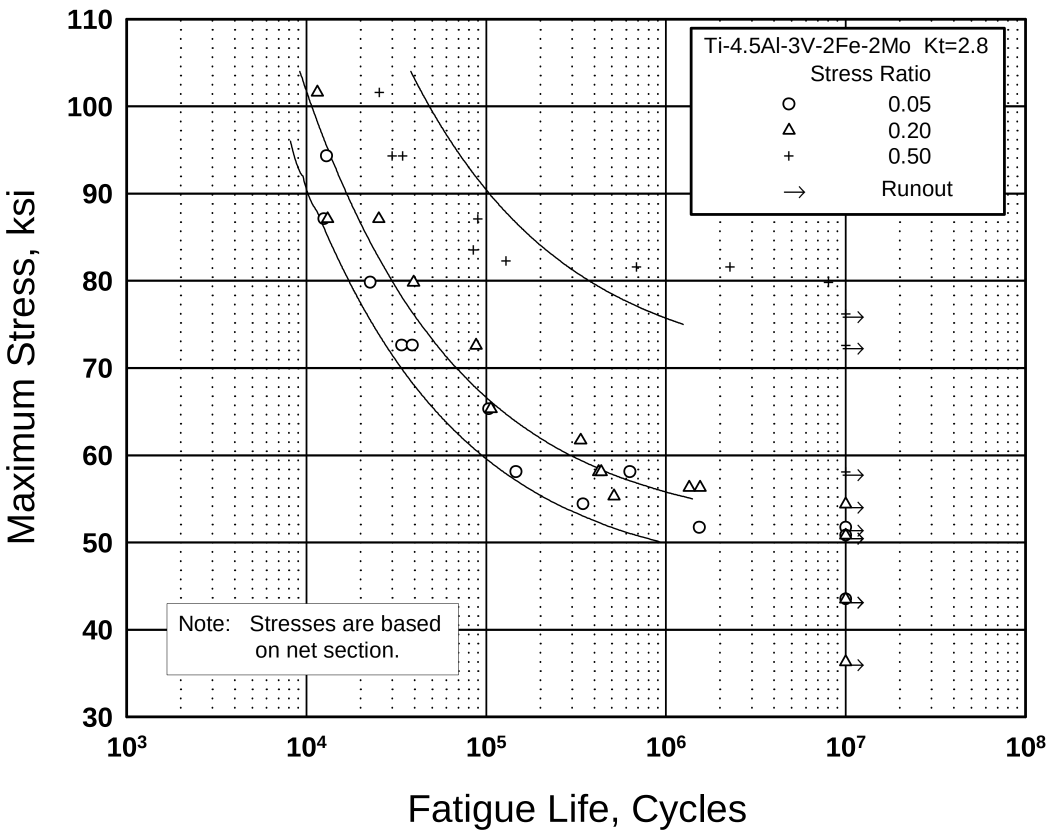

Figure 5.4.3.1.8 (b) Best-fit S/N curves for notched, Kt = 2.8, Ti-4.5Al-3V-2Fe-2Mo annealed sheet.

Correlative Information for Figure 5.4.3.1.8 (b)

Product Form: 0.059, 0.118, 0.157-inch thick

Properties:	TUS, ksi	TYS, ksi	Temp., °F
	148 - 149	135 - 138	RT

Specimen Details: Notched, Kt=2.8
0.466-inch net width

Surface Conditions: HF/HNO_3 pickled

References: 5.4.3.1.8

Test Parameter:
Loading - Axial
Frequency - 10Hz
Temperature - RT
Environment - Air

No. of Heats : 3

Equivalent Stress Equation:
$\text{Log } N_f = 7.22 - 1.96 \log (S_{eq} - 44.05)$
$S_{eq} = S_{max} (1 - R)^{0.65}$
Std. Error of Estimate, Log (Life) = 0.24
Standard Deviation, Log (Life) = 0.47
Adjusted R^2 = 72.9%

Sample Size : 41

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

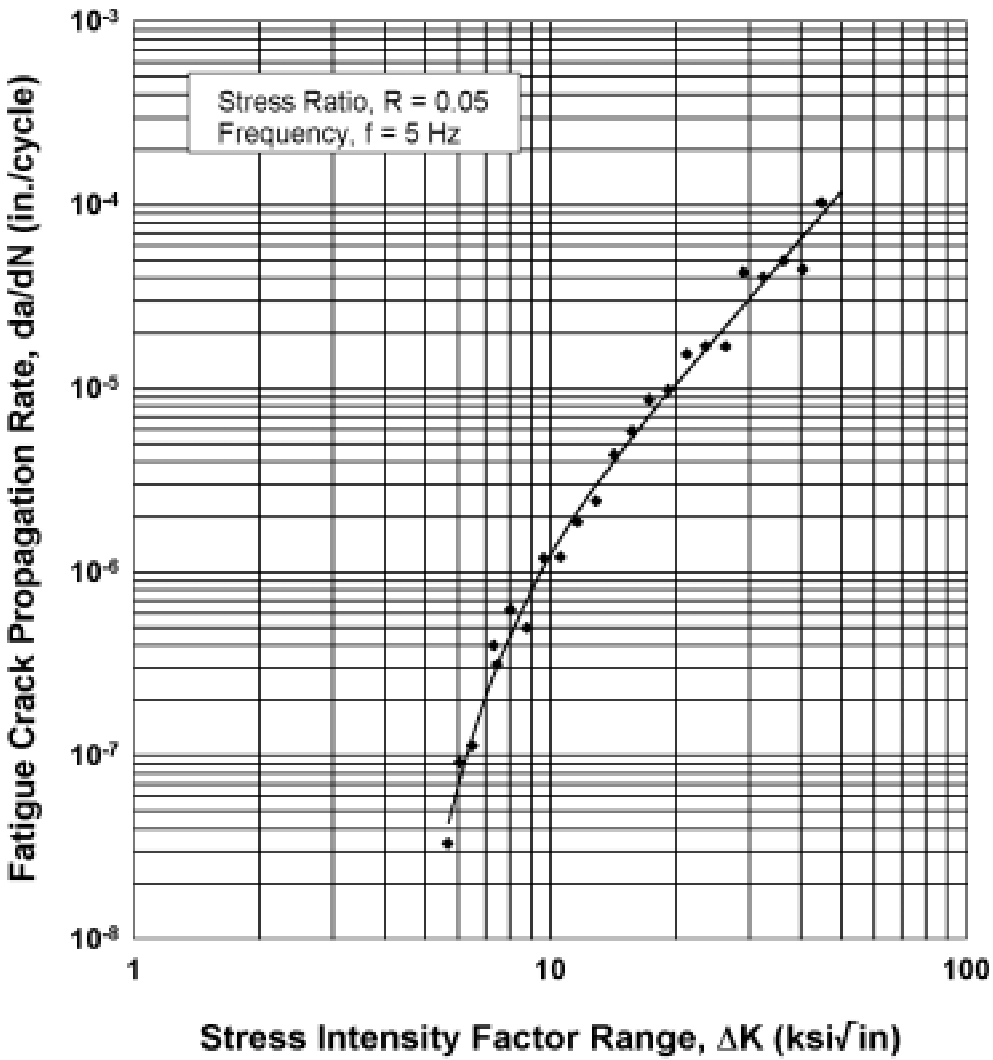

Figure 5.4.3.1.9 Fatigue-crack-propagation data for 1 inch thick Ti-4.5Al-3V-2Fe-2Mo mill annealed titanium alloy plate.

Specimen Thickness:	*0.25 inch*	*Environment:*	*50% RH*
Specimen Width:	*2.0 inches*	*Temperature:*	*RT*
Specimen Type:	*C(T)*	*Orientation:*	*L-T*

5.5 BETA, NEAR-BETA, AND METASTABLE-BETA TITANIUM ALLOYS

There is no clear-cut definition for beta titanium alloys. Conventional terminology usually refers to near-beta alloys and metastable-beta alloys as classes of beta titanium alloys. A near-beta alloy is generally one which has appreciably higher beta stabilizer content than a conventional alpha-beta alloy such as Ti-6Al-4V, but is not quite sufficiently stabilized to readily retain an all-beta structure with an air cool of thin sections. For such alloys, a water quench even of thin sections is required. Due to the marginal stability of the beta phase in these alloys, they are primarily solution treated below the beta transus to produce primary alpha phase which in turn results in an enriched, more stable beta phase. This enriched beta phase is more suitable for aging. The Ti-10V-2Fe-3Al alloy is an example of a near-beta alloy.

On the other hand, the metastable-beta alloys are even more heavily alloyed with beta stabilizers than near-beta alloys and, as such, readily retain an all-beta structure upon air cooling of thin sections. Due to the added stability of these alloys, it is not necessary to heat treat below the beta transus to enrich the beta phase. Therefore, these alloys do not normally contain primary alpha since they are usually solution treated above the beta transus. These alloys are termed “metastable” because the resultant beta phase is not truly stable—it can be aged to precipitate alpha for strengthening purposes. Alloys such as Ti-15-3, B120VCA, Beta C, and Beta III are considered metastable-beta alloys.

Unfortunately, the classification of an alloy as either near-beta or metastable beta is not always obvious. In fact, the “metastable” terminology is not precise since a near-beta alloy is also metastable—i.e., it also decomposes to alpha plus beta upon aging.

There is one obvious additional category of beta alloys—the stable beta alloys. These alloys are so heavily alloyed with beta stabilizers that the beta phase will not decompose to alpha plus beta upon subsequent aging. There are no such alloys currently being produced commercially. An example of such an alloy is Ti-30Mo.

The interest in beta alloys stems from the fact that they contain a high volume fraction of beta phase which can be subsequently hardened by alpha precipitation. Thus, these alloys can generate quite high-strength levels (in excess of 200 ksi) with good ductilities. Also, such alloys are much more deep hardenable than alpha-beta alloys such as Ti-6Al-4V. Finally, many of the more heavily alloyed beta alloys exhibit excellent cold formability and as such offer attractive sheet metal forming characteristics.

5.5.1 TI-13V-11CR-3AL

5.5.1.0 *Comments and Properties* — Ti-13V-11Cr-3Al is a heat-treatable alloy possessing good workability and toughness in the annealed condition and high strength in the heat-treated condition. It is noted for its exceptional ability to harden in heavy sections (up to 6-inch diameter or greater) to tensile strength of 170 ksi F_{tu}.

Manufacturing Considerations — This alloy possesses very good formability at room temperature; stretch forming is usually conducted at 500°F. Ti-13V-11Cr-3Al is readily fusion or spot welded. Arc-welded joints are very ductile in the as-welded condition, but have low strengths.

Environmental Considerations — Ti-13V-11Cr-3Al is stable for times up to 1000 hours in the annealed condition at 550°F and in the solution treated and aged condition up to 600°F. Prolonged exposure above these temperatures may result in ductility losses. If welding is employed, the stability of the weld should be investigated under the particular exposure conditions to be encountered. While the material is not noted for good creep performance, Ti-13V-11Cr-3Al has exceptional short-time strength at temperatures to 1200°F and above. Oxidation resistance is satisfactory at such temperatures for short-time exposure and for long-time exposure at the lower elevated temperatures. Hot-salt stress corrosion has been shown to be possible in this

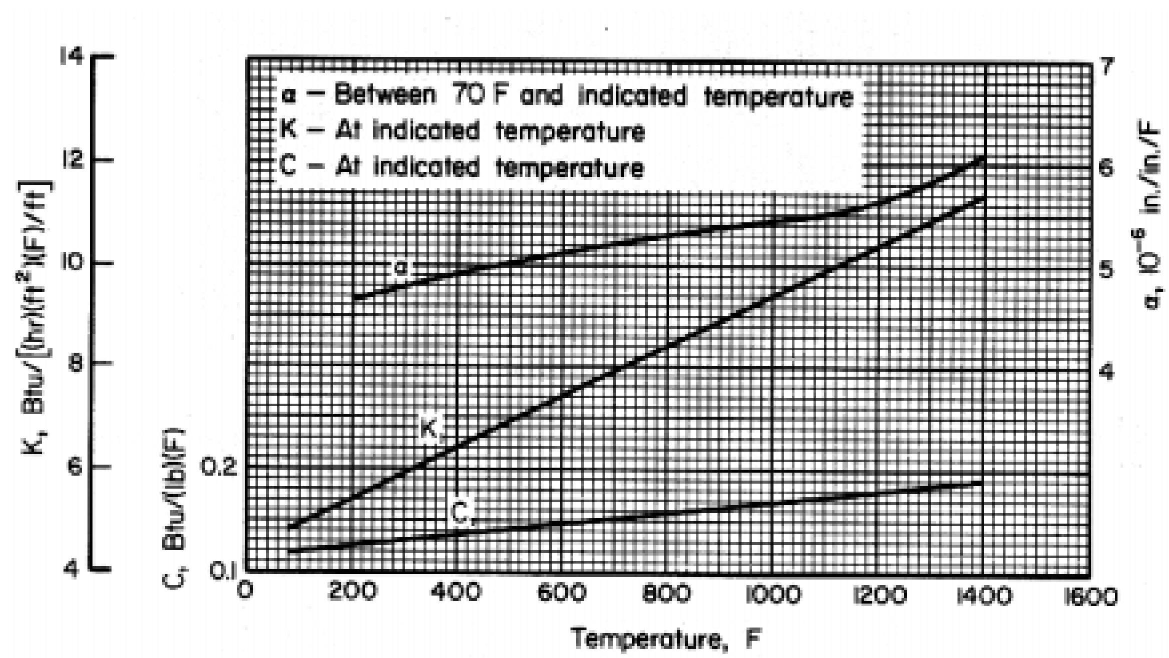

Figure 5.5.2.0. Effect of temperature on the physical properties of Ti-15V-3Cr-3Sn-3Al alloy.

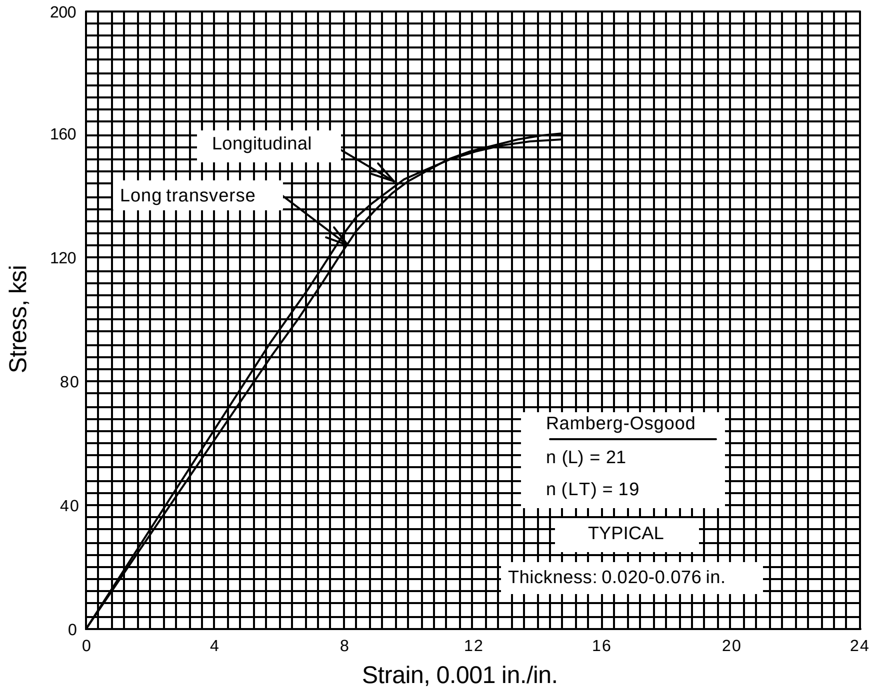

Figure 5.5.2.1.6(a). Typical tensile stress-strain curves at room temperature for solution treated and aged (1000EF) Ti-15V-3Cr-3Sn-3Al alloy sheet.

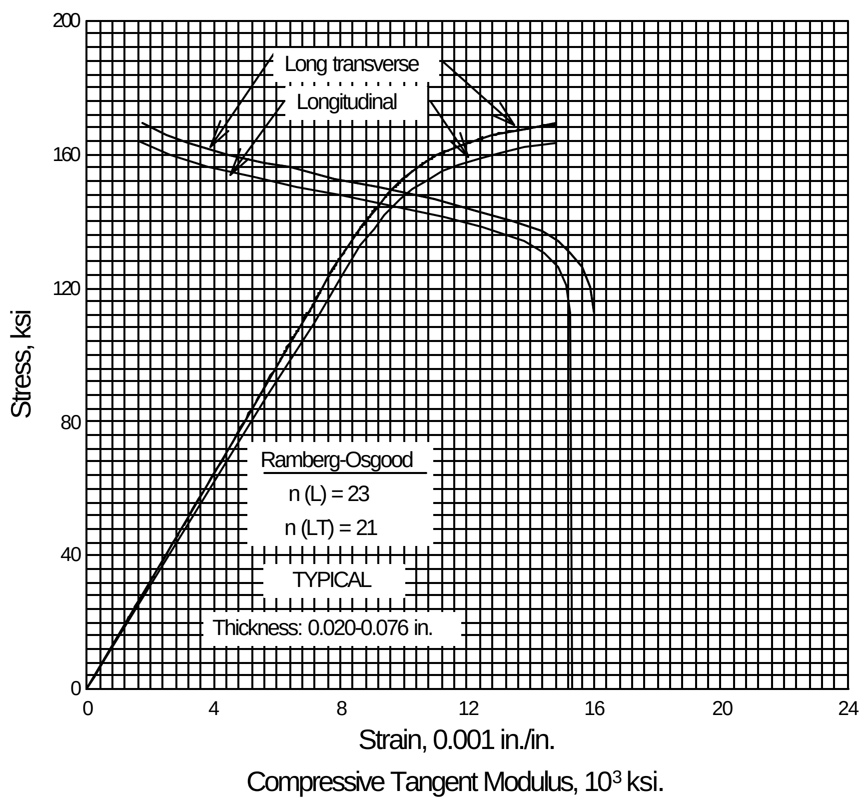

Figure 5.5.2.1.6(b). Typical compressive stress-strain and compressive tangent-modulus curves at room temperature for solution treated and aged (1000EF) Ti-15V-3Cr-3Sn-3Al alloy sheet.

Table 5.5.3.0(b). Design Mechanical and Physical Properties of Ti-10V-2Fe-3Al Die Forging

Specification	AMS 4983	AMS 4984
Form	Conventional die forging	
Condition	Solution treated and aged (900-950°F)	
Thickness, in.	<1.000	≤3.000
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	180	173
LT	180[a]	173[a]
ST	...	173[a]
F_{ty}, ksi:		
L	160	160
LT	160[a]	160[a]
ST	...	160[a]
F_{cy}, ksi:		
L	168	168
LT	166	166
ST	...	166
F_{su}, ksi	101	97
F_{bru}[b], ksi:		
(e/D = 1.5)	244	234
(e/D = 2.0)	295	284
F_{bry}[b], ksi:		
(e/D = 1.5)	227	227
(e/D = 2.0)	261	261
e, percent:		
L	4	4
LT	4[a]	4[a]
ST	...	4[a]
E, 10^3 ksi	15.9	
E_c, 10^3 ksi	16.3	
G, 10^3 ksi	...	
μ	...	
Physical Properties:		
ω, lb/in.^{3}	0.168	
a, 10^{-6} in./in./°F	5.4 (68-800°F)	
C and K	...	

a Applicable providing LT or ST dimension is ≥2.500 inches.
b Bearing values are "dry pin" values per Section 1.4.7.1.

Table 5.5.3.0(c). Design Mechanical and Physical Properties of Ti-10V-2Fe-3Al Hand Forging

Specification	AMS 4986	
Form	Hand forging	
Condition	Solution treated and aged (950-1000°F)	
Thickness, in.	$\leq$3.000	3.001-4.000
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	160	160
LT	160[a]	160
F_{ty}, ksi:		
L	145	145
LT	145[a]	145
F_{cy}, ksi:		
L	154	...
LT	...	...
F_{su}, ksi	97[b]	...
F_{bru}[c], ksi:		
(e/D = 1.5)	241	...
(e/D = 2.0)	293	...
F_{bry}[c], ksi:		
(e/D = 1.5)	218	...
(e/D = 2.0)	245	...
e, percent:		
L	6	6
LT	6[a]	6
RA, percent:		
L	10	10
LT	10[a]	10
E, 10^3 ksi	15.9	
E_c, 10^3 ksi	16.3	
G, 10^3 ksi	...	
μ	...	
Physical Properties:		
ω, lb/in.^{3}	0.168	
a, 10^{-6} in./in./°F	5.4 (68-800°F)	
C and K	...	

a Applicable providing LT dimension is $\geq$2.500 inches.
b Shear strength determined in accordance with ASTM B 769.
c Bearing values are "dry pin" per Section 1.4.7.1.

5.4.1.1.8(a) "Fatigue Evaluation of Ti-6Al-4V Bar Stock", Sikorsky Aircraft, Report No. SER-50631 (MIL-HDBK-5 Source M-459) (March 1970).

5.4.1.1.8(b) Brockett, R. M., and Gottbrath, J. A., "Development of Engineering Data on Titanium Extrusion for Use in Aerospace Design", Lockheed-California Co., Technical Report AFML-TR-67-189 (July 1967) (MCIC 69807, MIL-HDBK-5 Source M-543).

5.4.1.1.8(c) Rhode, T. M., and Ertel, P. W., "Constant Amplitude Fatigue Life Data for Notched and Unnotched Annealed Ti-6Al-4V Sheet", AFWAL-TR-88-4081, January 1988 (MIL-HDBK-5 Source M-696).

5.4.1.1.9 Fedderson, C. E., and Hyler, W. S., "Fracture and Fatigue-Crack Propagation Characteristics of ¼-Inch Mill Annealed Ti-6Al-4V Titanium Alloy Plate", Report No. G9706, Battelle, Columbus, Ohio (1971).

5.4.1.2.8(a) "Fatigue Strength Properties for Heat Treated Ti-4Al-30Mo-1V and Ti-6Al-4V Titanium Alloys (LP-69-132 and LP-69-129)", North American Aviation, Report No. TFD-60-521 (July 18, 1960) (MCIC 65737).

5.4.1.2.8(b) "Determination of Design Data for Heat Treated Titanium Alloy Sheet", Lockheed-Georgia Co., Report No. ASD-TDR-62-335, Vol. 3, Contract No. AF33(616)-6346 (May 1962) (MCIC 90172).

5.4.1.2.8(c) Sommer, A. W., and Martin, G. R., "Design Allowables for Titanium Alloys", North American Rockwell, AFML-TR-69-161 (June 1969) (MCIC 75727).

5.4.1.2.8(d) Marrocco, A. G., "Fatigue Characteristics of Ti-6Al-4V and Ti-6Al-6V-2Sn Sheet and Plate", Grumman Aircraft Engineering Corp., EMG-81 (November 18, 1968) (MCIC 76303).

5.4.1.2.8(e) Sargent, M. R., "Fatigue Characteristics of Ti-6Al-4V Plate and Forgings (SWIP)", General Dynamics, FGT-3218 (September 22, 1965) (MIL-HDBK-5 Source M-457).

5.4.2.1.8 Marrocco, A. G., "Evaluation of Ti-6Al-4V and Ti-6Al-6V-2Sn Forgings", Grumman Aircraft Engineering Corporation, EMG-82, November 1968 (MIL-HDBK-5 Source M-522).

5.4.3.1 Unpublished data from NKK, January 2001, (MIL-HDBK-5 Source M-914).

5.5.1 Henning, R. G., "Mechanical Properties of Solution-Treated Titanium Sheet Alloy B120VCA", ASD TR 61-337 (September 1961).

5.5.1.1.8 Blatherwick, A. A., "Fatigue, Creep, and Stress-Rupture Properties of Ti-13V-11Cr-3Al Titanium Alloy (B120VCA)", AFML-TR-66-293 (September 1966).

5.5.1.2.8 Schwartzberg, F. R., Kiefer, T. F., and Keys, R. D., "Determination of Low-Temperature Fatigue Properties of Structural Metal Alloys 1 April 1962 through 30 September 1964", Martin-Cr-64-74 (October 1964), pp 158 (MCIC 58024).

5.6(a) "Theoretical and Experimental Determination of the Bending Modulus of Rupture for Round Titanium Tubing", Bendix Products Division (July 31, 1958).

5.6(b) Cozzone, F. P., "Bending Strength in Plastic Range", *Journal of the Aeronautical Sciences* (May 1943).

5.6(c) Ades, C. S., "Bending Strength of Tubing in the Plastic Range", *Journal of Aeronautical Sciences* (August 1957).

5.6(d) "Theoretical and Experimental Determination of the Bending Modulus of Rupture of Round Titanium Tubing", Systems Engineering Report, Bendix Energy Controls Division, South Bend, Indiana, MS-58-3 (July 1958).

6.1.1 MATERIAL PROPERTIES

6.1.1.1 *Mechanical Properties* — The mechanical properties of the heat-resistant alloys are affected by relatively minor variations in chemistry, processing, and heat treatment. Consequently, the mechanical properties shown for the various alloys in this chapter are intended to apply only to the alloy, form (shape), size (thickness), and heat treatment indicated. When statistical values are shown, these are intended to represent a fair cross section of all mill production within the indicated scope.

Strength Properties — Room-temperature strength properties for alloys in this chapter are based primarily on minimum tensile property requirements of material specifications. Values for nonspecification strength properties are derived. The variation of properties with temperature and other data or interest are presented in figures or tables, as appropriate.

The strength properties of the heat-resistant alloys generally decrease with increasing temperatures or increasing time at temperature. There are exceptions to this statement, particularly in the case of age-hardening alloys; these alloys may actually show an increase in strength with temperature or time, within a limited range, as a result of further aging. In most cases, however, this increase in strength is temporary and, furthermore, cannot usually be taken advantage of in service. For this reason, this increase in strength has been ignored in the preparation of elevated temperature curves as described in Chapter 9.

At cryogenic temperatures, the strength properties of the heat-resistant alloys are generally higher than at room temperature, provided some ductility is retained at the low temperatures. For additional information on mechanical properties at cryogenic temperatures, other references, such as the Cryogenic Materials Data Handbook (Reference 6.1.1.1), should be consulted.

Ductility — Specified minimum ductility requirements are presented for these alloys in the room-temperature property tables. The variation in ductility with temperature is somewhat erratic for the heat-resistant alloys. Generally, ductility decreases with increasing temperature from room temperature up to about 1200 to 1400°F, where it reaches a minimum value, then it increases with higher temperatures. Prior creep exposure may also affect ductility adversely. Below room temperature, ductility decreases with decreasing temperature for some of these alloys.

Stress-Strain Relationships — The stress-strain relationships presented are typical curves prepared as described in Section 9.3.2.

Creep — Data covering the temperatures and times of exposure and the creep deformations of interest are included as typical information in individual material sections. These presentations may be in the form of creep stress-lifetime curves for various deformation criteria as specified in Chapter 9 or as creep nomographs.

Fatigue — Fatigue S/N curves for unnotched and notched specimens at room temperature and elevated temperatures are shown in each alloy section. Fatigue crack propagation data are also presented.

6.1.1.2 *Physical Properties* —Selected physical-property data are presented for these alloys. Processing variables and heat treatment have only a slight effect on these values; thus, the properties listed are applicable to all forms and heat treatments.

6.2 IRON-CHROMIUM-NICKEL-BASE ALLOYS

6.2.0 GENERAL COMMENTS — The alloys in this group, in terms of cost and in maximum service temperature, generally fall between the austenitic stainless steels and the nickel- and cobalt-base alloys. They are used in airframes, principally, in the temperature range 1000 to 1200°F, in those applications in which the stainless steels are inadequate and service requirements do not justify the use of the more costly nickel or cobalt alloys.

6.2.0.1 *Metallurgical Considerations*

Composition — The complex-base alloys comprising this group range from those in which iron is considered the base element to those which border on the nickel-base alloys. All of them contain sufficient alloying elements to place them in the "Superalloy" category, yet contain enough iron to reduce their cost considerably.

Chromium, in amounts ranging from 10 to 20 percent or higher, primarily increases oxidation resistance and contributes to strengthening of these alloys. Nickel and cobalt strengthen and toughen these materials. Molybdenum, tungsten, and columbium contribute to hardness and strength, particularly at elevated temperatures. Titanium and aluminum are added to provide age-hardening.

Heat Treatment — The complex-base alloys are heat treated with conventional equipment and fixtures such as would be used for austenitic stainless steels. Since these alloys are susceptible to carburization during heat treatment, it is good practice to remove all grease, oil, cutting, lubricant, etc., from the surface before heating. A low-sulfur and neutral or slightly oxidizing furnace atmosphere is recommended for heating.

6.2.0.2 *Manufacturing Considerations* — The iron-chromium-nickel-base alloys closely resemble the austenitic stainless steels insofar as forging, cold forming, machining, welding, and brazing are concerned. Their higher strength may require the use of heavier forging or forming equipment, and machining is somewhat more difficult than for the stainless steels. Pertinent comments are included under the individual alloys.

6.2.1 A-286

6.2.1.0 *Comments and Properties* — A-286 is a precipitation-hardening iron-base alloy designed for parts requiring high strength up to 1300°F and oxidation resistance up to 1500°F. It is used in jet engines and gas turbines for parts such as turbine buckets, bolts, and discs, and sheet metal assemblies. A-286 is available in the usual mill forms.

A-286 is somewhat harder to hot or cold work than the austenitic stainless steels. Its forging range is 2150 to 1800°F; when finishing below 1800°F, light reductions (under 15 percent) must be avoided to prevent grain coarsening during subsequent heat treatment. A-286 is readily machined in the partially or fully aged condition but is soft and "gummy" in the solution-treated condition. A-286 should be welded in the solution-treated condition. Fusion welding is difficult for large section sizes and moderately difficult for small cross sections and sheet. Cracking may be encountered in the welding of heavy sections or parts under high restraint. A dimensional contraction of 0.0008 inch per inch is experienced during aging. Oxidation resistance of A-286 is equivalent to that of Type 310 stainless steel up to 1800°F.

Some material specifications for A-286 alloy are presented in Table 6.2.1.0(a). Room-temperature mechanical and physical properties are shown in Table 6.2.1.0(b). The effect of temperature on physical properties is shown in Figure 6.2.1.0.

6.2.1.1 *Solution-Treated and Aged Condition* — Elevated-temperature data are presented in Figures 6.2.1.1.1, 6.2.1.1.3, and 6.2.1.1.4(a) through (c). Stress rupture properties are specified at 1200°F; the appropriate specifications should be consulted for detailed requirements. Figures 6.2.1.1.8(a) through (e) are fatigue S/N curves for several elevated temperatures.

Table 6.2.1.0(a). Material Specifications for A-286 Alloy

Specification	Form	Condition
AMS 5525	Sheet, strip, and plate	Solution treated (1800°F)
AMS 5731	Bar, forging, tubing, and ring	Solution treated (1800°F)
AMS 5732	Bar, forging, tubing, and ring	Solution treated (1800°F) and aged
AMS 5734	Bar, forging, and tubing	Solution treated (1650°F)
AMS 5737	Bar, forging, and tubing	Solution treated (1650°F) and aged

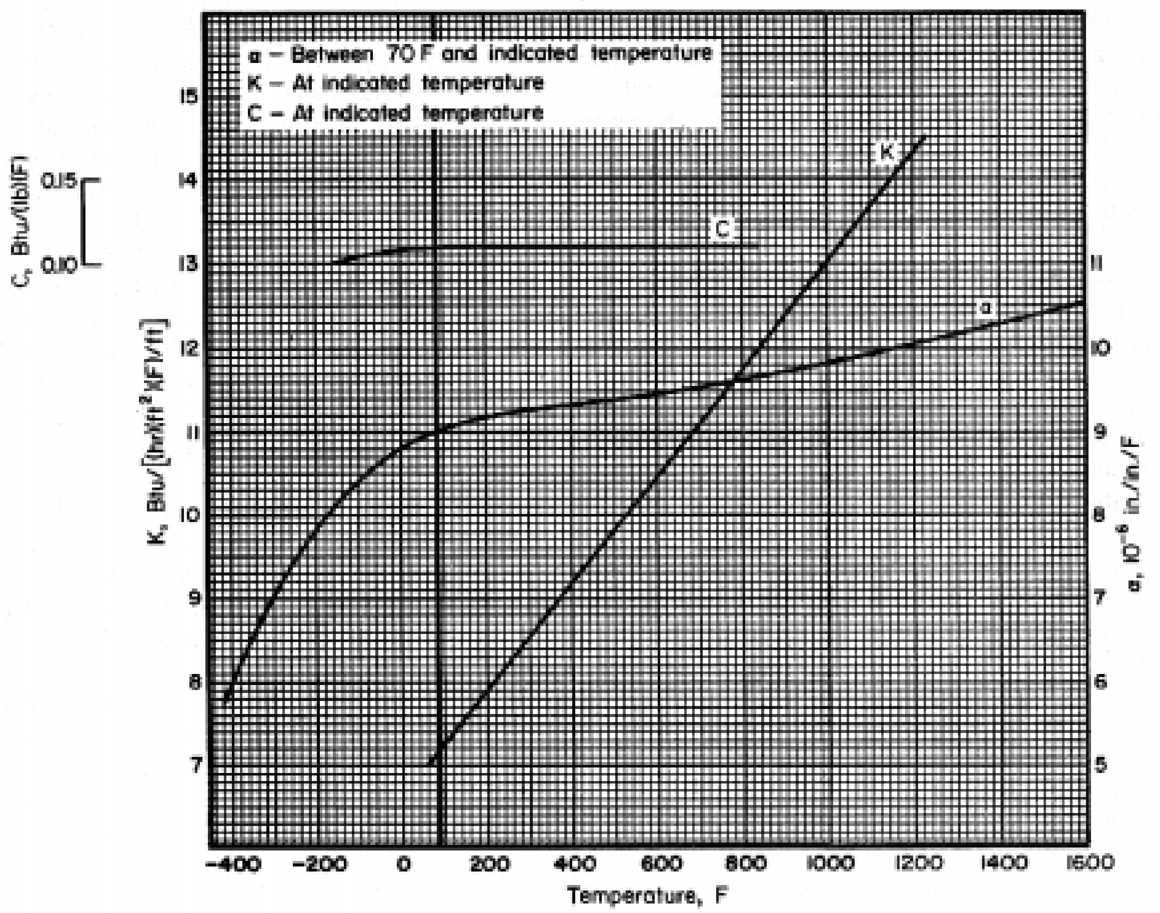

Figure 6.2.1.0. Effect of temperature on the physical properties of A-286.

Table 6.2.1.0(b). Design Mechanical and Physical Properties of A-286 Alloy

Specification	AMS 5525	AMS 5731 AMS 5732		AMS 5734 AMS 5737	
Form	Sheet, strip, and plate	Bar			
Condition	Solution treated and aged				
Thickness or diameter, in.	>0.004	≤2.499	2.500-5.000	≤2.499	2.500-5.000
Basis	S[a]	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	...	130	130	140	140
LT	140	130[b]	130	140[b]	140
ST	...	...	130	...	140
F_{ty}, ksi:					
L	...	85	85	95	95
LT	95	85[b]	85	95[b]	95
ST	...	...	85	...	95
F_{cy}, ksi:					
L	...	85	85	95	95
LT	95	...	...	...	...
F_{su}, ksi	91	85	85	91	91
F_{bru}, ksi:					
(e/D = 1.5)	210	195	195	210	210
(e/D = 2.0)	266	247	247	266	266
F_{bry}, ksi:					
(e/D = 1.5)	142	127	127	142	142
(e/D = 2.0)	171	153	153	171	171
e, percent:					
L	...	15	15	12	12
LT	15	15[b]	15	12[b]	12
ST	...	...	15	...	12
RA, percent:					
L	...	20	20	15	15
LT	...	20[b]	20	15[b]	15
ST	...	...	20	...	15
E, 10^3 ksi	29.1				
E_c, 10^3 ksi	29.1				
G, 10^3 ksi	11.1				
μ	0.31				
Physical Properties:					
ω, lb/in.^{3}	0.287				
C, K, and α	See Figure 6.2.1.0				

a Test direction longitudinal for widths less than 9 inches; transverse for widths 9 inches and over.
b Applicable to widths ≥2.500 inches only.

6.3.5 INCONEL 718

6.3.5.0 *Comments and Properties* — Inconel 718 is a vacuum-melted, precipitation-hardened nickel-base alloy. It can be welded easily and excels in its resistance to strain-age cracking. It is also readily formable. Depending on choice of heat treatments, this alloy finds applications requiring either (1) high resistance to creep and stress rupture to 1300°F or (2) high strength at cryogenic temperatures. It also has good oxidation resistance up to 1800°F. Inconel 718 is available in all wrought forms and investment castings.

Because of the close relationship between heat treatment, properties, and applications, both the product form and application are listed with the specifications in Table 6.3.5.0(a). Room-temperature mechanical and physical properties are presented in Tables 6.3.5.0(b) through (d). The effect of temperature on physical properties is presented in Figure 6.3.5.0.

Table 6.3.5.0(a). Material Specifications for Inconel 718

Specification	Form	Application
AMS 5589	Tubing	Creep-rupture
AMS 5590	Tubing	Short-time
AMS 5596	Sheet, strip, plate	Creep-rupture
AMS 5597	Sheet, strip, plate	Short-time
AMS 5662, 5663	Bar, forging	Creep-rupture
AMS 5664	Bar, forging	Short-time
AMS 5383	Investment castings	Short-time

6.3.5.1 *Solution-Treated and Aged Condition* — Elevated-temperature curves are presented in Figures 6.3.5.1.1 and 6.3.5.1.4(a) through (c). Typical tensile and compressive stress-strain curves as well as typical compressive tangent-modulus curves for sheet and castings are shown in Figures 6.3.5.1.6(a) through (c). Figure 6.3.5.1.6(d) is a typical stress-strain curve (full range) for Inconel 718 investment casting. Creep and stress-rupture curves for forging are shown in Figures 6.3.5.1.7(a) through (e). Supplemental creep and stress-rupture information for forging is presented in Table 6.3.5.1.7. Fatigue S/N curves are presented in Figures 6.3.5.1.8(a) through (g). Fatigue-crack-propagation data for die forging and plate are presented in Figures 6.3.5.1.9(a) through (c).

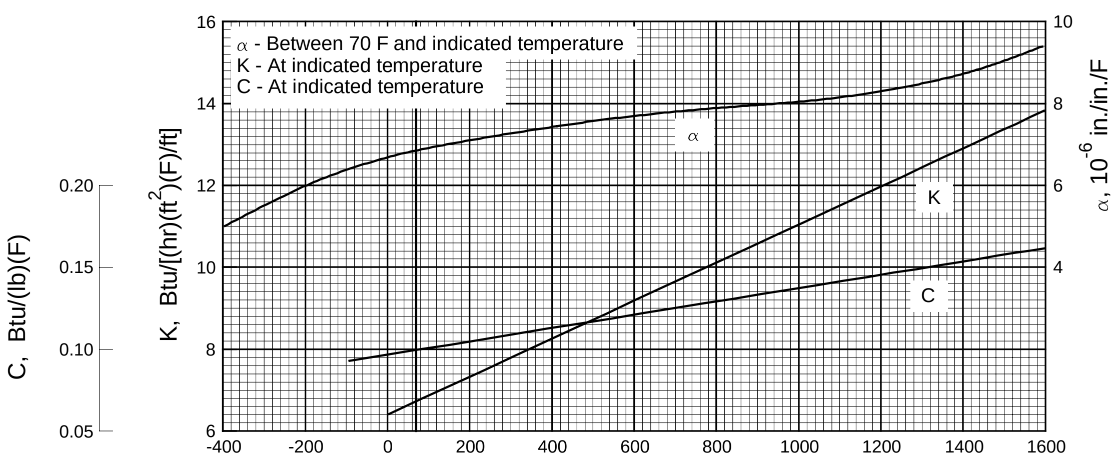

Figure 6.3.5.0. Effect of temperature on the physical properties of Inconel 718.

Table 6.3.5.0(b). Design Mechanical and Physical Properties of Inconel 718

Specification	AMS 5596				AMS 5597	AMS 5589	AMS 5590
Form	Sheet		Plate		Sheet and plate	Tubing	
Condition	Solution treated and aged per indicated specification						
Thickness, in.	0.010-0.187		0.188-0.249	0.250-1.000	0.010-1.000	O.D. > 0.125 Wall > 0.015	
Basis	A	B	S	S	S	S	S
Mechanical Properties[a]:							
F_{tu}, ksi:							
L	180	192	180	...	...	185	170
LT	180[b]	191	180	180	180	...	...
F_{ty}, ksi:							
L	145	156	148	...	...	150	145
LT	147	158	150	150	150	...	...
F_{cy}, ksi:							
L	155	167	158	...	...	...	...
LT	158	170	161	...	...	...	...
F_{su}, ksi	124	132	124	...	...	...	...
F_{bru}[c], ksi:							
(e/D = 1.5)	291	309	291	...	...	...	...
(e/D = 2.0)	380	403	380	...	...	...	...
F_{bry}[c], ksi:							
(e/D = 1.5)	208	223	212	...	...	...	...
(e/D = 2.0)	241	259	246	...	...	...	...
e, percent (S-basis):							
L	...	...	...	...	...	12	15
LT	12	...	12	12	12	...	...
E, 10^3 ksi	29.4						
E_c, 10^3 ksi	30.9						
G, 10^3 ksi	11.4						
μ	0.29						
Physical Properties:							
ω, lb/in.^{3}	0.297						
C, K, and α	See Figure 6.3.5.0						

a Design allowables were based upon data from samples of material, supplied in the solution treated condition, which were aged to demonstrate heat treatment response by suppliers. Properties obtained by the user may be different, if the material has been formed or otherwise cold worked.
b S-basis. The rounded T_{99} value is 183 ksi.
c Bearing values are "dry pin" values per Section 1.4.7.1.

Table 6.3.5.0(c). Design Mechanical and Physical Properties of Inconel 718 Bar and Forging

Specification	AMS 5662 and AMS 5663								AMS 5664	
Form	Bar							Forging	Bar	Forging
Condition	Solution treated and aged per indicated specification									
Thickness, in.	0.250-1.000	1.001-1.500	1.501-2.000	2.001-2.500	2.501-3.000	3.001-4.000	4.001-5.000	≤5.000	≤10.000	≤10.000
Basis	S	S	S	S	S	S	S	S	S	S
Mechanical Properties:										
F_{tu}, ksi:										
L	185	185	185	185	185	185	185	185	185	180
LT[a]	180	180	180	180	180	180	180	180	180	180
ST[a]	...	...	...	...	180	180	180	...	...	180
F_{ty}, ksi:										
L	150	150	150	150	150	150	150	150	150	150
LT[a]	150	150	150	150	150	150	150	150	150	150
ST[a]	...	...	...	...	146	150	150	...	...	150
F_{cy}, ksi:										
L	156	156	156	156	156	156	156	...	...	...
ST	...	...	...	156	156	156	156	...	...	...
F_{su}, ksi	111	114	116	118	119	121	123	...	...	...
F_{bru}[b], ksi:										
(e/D = 1.5)	309	309	309	309	309	309	309	...	...	...
(e/D = 2.0)	394	394	394	394	394	394	394	...	...	...
F_{bry}[b], ksi:										
(e/D = 1.5)	216	216	216	216	216	216	216	...	...	...
(e/D = 2.0)	257	257	257	257	257	257	257	...	...	...
e, percent:										
L	12	12	12	12	12	12	12	12	10	12
LT[b]	6	6	6	6	6	6	6	10	10	12
ST[b]	...	...	...	...	6	6	6	...	10	12
RA, percent:										
L	15	15	15	15	15	15	15	15	12	15
LT[b]	8	8	8	8	8	8	8	12	12	15
ST[b]	...	...	...	...	8	8	8	...	12	15
E, 10^3 ksi:	29.4									
E_c, 10^3 ksi:	30.9									
G, 10^3 ksi	11.4									
μ	0.29									
Physical Properties:										
ω, lb/in.^{3}	0.297									
C, K, and α	See Figure 6.3.5.0									

a Applicable providing LT or ST direction is ≥2.500 inches.
b Bearing values are “dry pin” values per Section 1.4.7.1.

Table 6.3.5.0(d). Design Mechanical and Physical Properties of Inconel 718 Investment Castings

Specification	AMS 5383
Form	Investment Casting
Condition	ST
Location within casting	Any
Thickness, in.	≤0.500
Basis	S
Mechanical Properties:	
F_{tu}, ksi	120
F_{ty}, ksi	105
F_{cy}, ksi	105
F_{su}, ksi	88[a]
F_{bru}[b], ksi:	
(e/D = 1.5)	202
(e/D = 2.0)	248
F_{bry}[b], ksi:	
(e/D = 1.5)	161
(e/D = 2.0)	188
e, percent	3
RA, percent	8
E, 10^3 ksi	29.4
E_c, 10^3 ksi	30.9
G, 10^3 ksi	11.4
μ	0.29
Physical Properties:	
ω, lb/in.^{3}	0.297
C, K, and α	See Figure 6.3.5.0

a Determined in accordance with ASTM Procedure B769.
b Bearing values are "dry pin" values per Section 1.4.7.1.

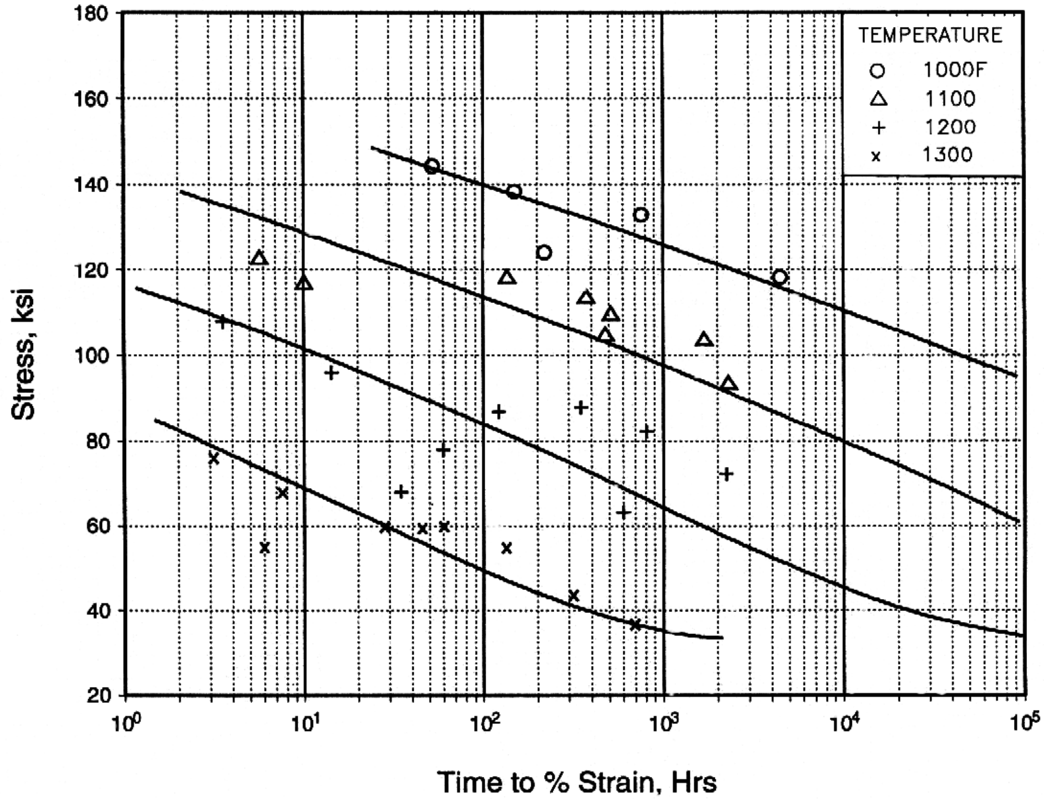

Figure 6.3.5.1.7(a). Average isothermal 0.10% creep curves for Inconel 718 forging.

Correlative Information for Figure 6.3.5.1.7(a)

Makeup of Data Collection:

Heat Treatment: 2 [See Table 6.3.5.1.7(f)]
Number of Vendors = Unknown
Number of Lots = 2
Number of Test Laboratories = 1
Number of Tests = 32

Specimen Details:

Type - Unnotched round bar
Gage Length - N.A.
Gage Thickness - 1/4" - 3/8"

0.10 Percent Creep Equation:

$$\text{Log } t = c + b_1 T + b_2 X + b_3 X^2 + b_4 X^3$$

T = ER
X = log (stress, ksi)
c = 185.16
b_1 = -0.01778
b_2 = -255.25
b_3 = 146.28
b_4 = -28.65

Analysis Details:

Inverse Matrix = [See Table 6.3.5.1.7(f)]
Std. Error of Estimate, Log (Hrs) = 0.56
Standard Deviation, Log (Hrs) = 0.99
R^2 = 68%

[Caution: The creep rupture model may provide unrealistic predictions for temperatures and stresses beyond those represented above.]

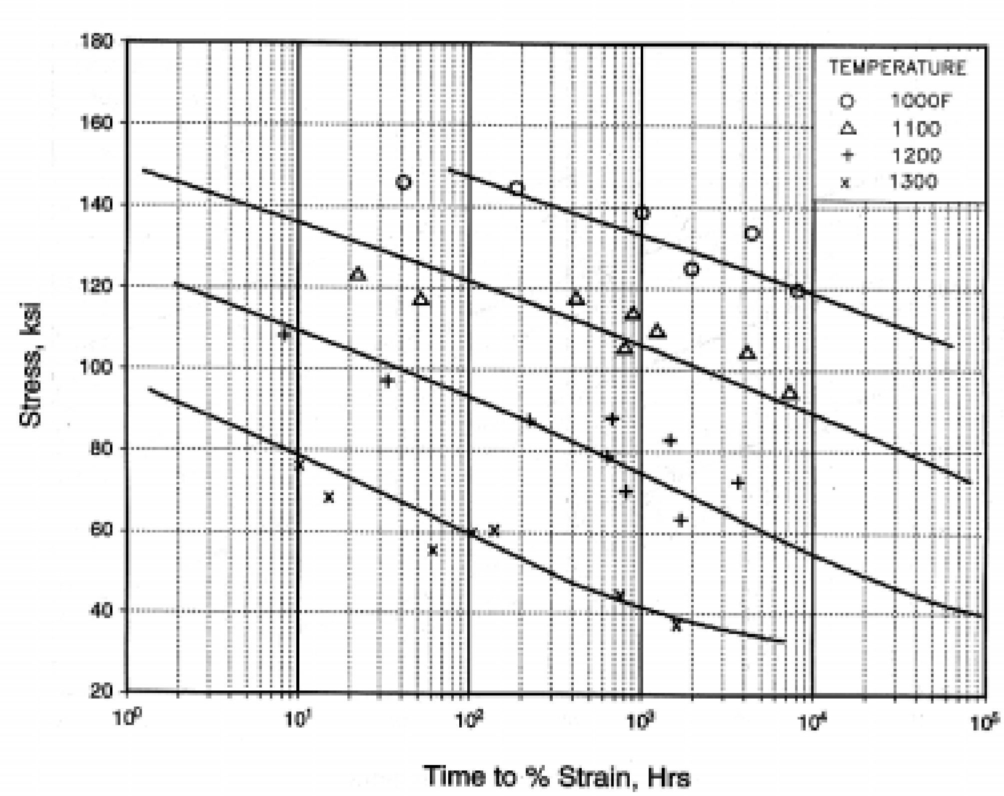

Figure 6.3.5.1.7(b). Average isothermal 0.20% creep curves for Inconel 718 forging.

Correlative Information for Figure 6.3.5.1.7(b)

Makeup of Data Collection:

Heat Treatment: 2 [See Table 6.3.5.1.7(f)]
Number of Vendors = Unknown
Number of Lots = 2
Number of Test Laboratories = 1
Number of Tests = 31

Specimen Details:

Type - Unnotched round bar
Gage Length - N.A.
Gage Thickness - 1/4" - 3/8"

0.20 Percent Creep Equation:

$\text{Log } t = c + b_1 T + b_2X + b_3X^2 + b_4X^3$
$T = {}^\circ R$
$X = \log(\text{stress, ksi})$
$c = 185.67$
$b_1 = -0.01778$
$b_2 = -255.25$
$b_3 = 146.28$
$b_4 = -28.65$

Analysis Details:

Inverse Matrix = [See Table 6.3.5.1.7(f)]
Standard Deviation = 0.98
Standard Error of Estimate = 0.41

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

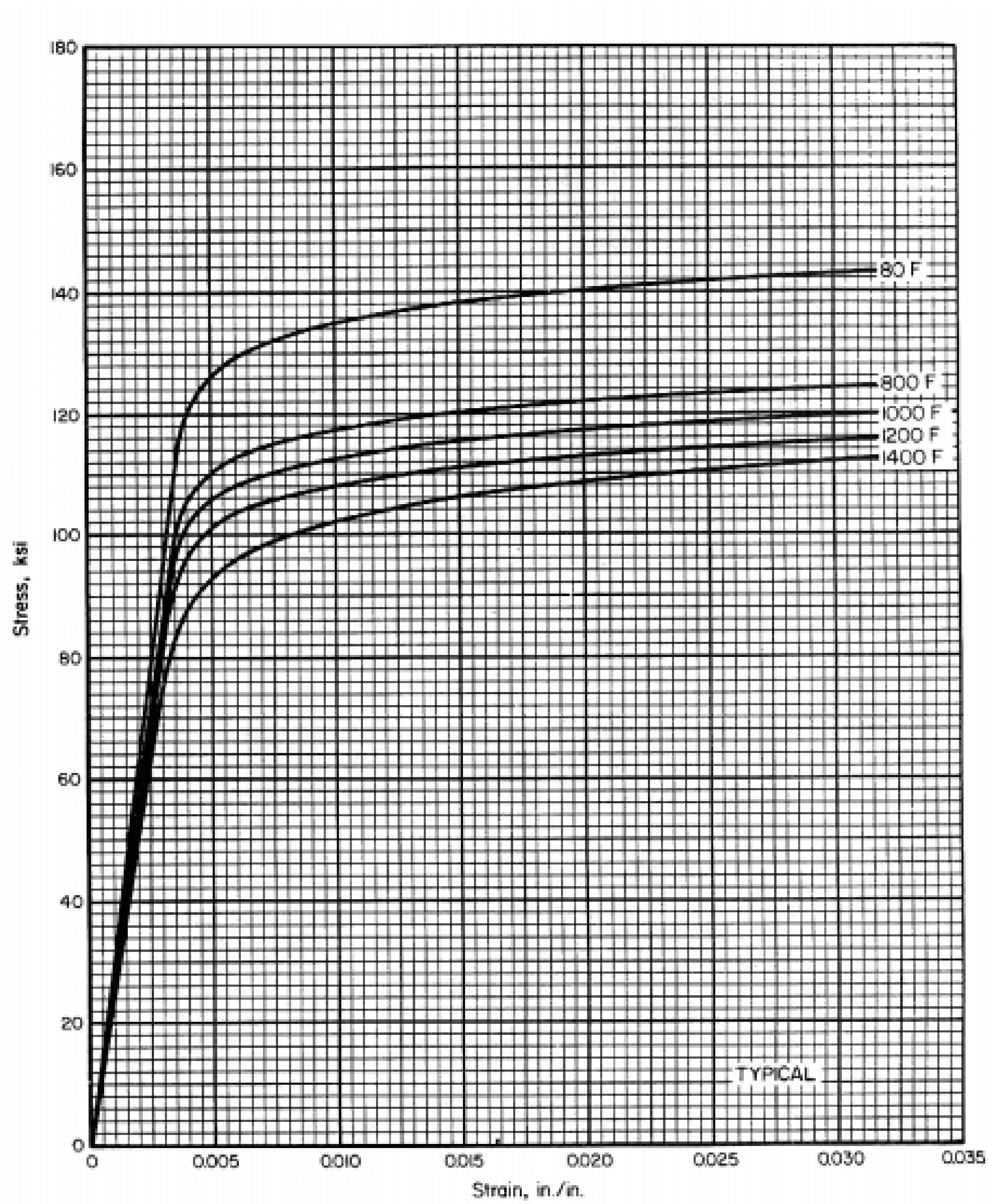

Figure 6.3.8.1.6(b). Typical tensile stress-strain curves for Waspaloy at room and elevated temperatures (all products).

6.3.9. HAYNES® 230®*

6.3.9.0. *Comments and Properties* — HAYNES® 230® alloy provides excellent oxidation resistance up to 2100°F for prolonged exposures with superior long term stability, high temperature strength and good fabricability. It is produced in the form of plate, sheet, strip, foil, billet, bar, wire welding products, pipe, tubing, remelt bar, and may be cast using traditional air-melt sand mold or vacuum-melt investment foundry techniques. Products are used for gas turbine components in the aerospace industry, catalyst grid supports in the chemical process industry, and various other high-temperature applications.

Environmental Considerations — HAYNES® 230® alloy has excellent corrosion resistance to both air and combustion gas oxidizing environments. It also exhibits excellent nitriding resistance and good resistance to carburization and hydrogen embrittlement.

Machining — HAYNES® 230® alloy has similar machining characteristics to other solid-solution-strengthened nickel-based alloys. This group of materials is classified moderate to difficult to machine, however, they can be machined using conventional methods at satisfactory rates. They work-harden rapidly, requiring slower speeds and feeds with heavier cuts than would be used for machining stainless steels. See HAYNES® publication H-3159 for more detailed information.

Joining — HAYNES® 230® alloy has excellent forming and welding characteristics similar to HASTELLOY® X alloy. It is readily welded using GTAW (Gas Tungsten-Arc Welding), GMAW (Gas Metal-Arc Welding), SMAW (Shielded Metal-Arc Welding), and resistance techniques. HAYNES® 230-W™ alloy is the recommended filler metal.

Heat Treatment — This alloy is normally final solution heat-treated between 2150°F and 2275°F. Annealing during fabrication can be performed at slightly lower temperatures, but a final subsequent solution heat treatment followed by rapid cooling is needed to produce optimum properties and structure.

Specifications and Properties — Material specifications are shown in Table 6.3.9.0(a).

Table 6.3.9.0(a). Material Specifications for HAYNES® 230® Alloy Wrought

Specification	Form
AMS 5878	Plate, sheet, and strip
AMS 5891	Bar and forging

Room temperature mechanical and physical properties are shown in Tables 6.3.9.0(b) and (c). Elevated temperature mechanical properties are shown in Figures 6.3.9.0(d) and (e).

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Table 6.3.9.0(b). Design Mechanical and Physical Properties of HAYNES® 230® Alloy Sheet and Plate

Specification	AMS 5878					
Form	Sheet		Plate			
Condition	2250 Anneal		2200 Anneal			
Thickness or diameter, in.	≤0.125		≤0.400		0.401 to 1.500	
Basis	A	B	A	B	A	B
Mechanical Properties:						
F_{tu}, ksi:						
L	...	...	...	...	...	...
LT	114	117	115[a]	120	111	114
F_{ty}, ksi:						
L	...	...	...	...	...	...
LT	49	53	50	55	48	51
F_{cy}, ksi:						
L	...	...	...	...	...	...
LT	...	...	...	...	...	...
F_{su}, ksi						
F_{bru}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
F_{bry}, ksi:						
(e/D = 1.5)	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...
e, percent:						
LT	39	42	40	43	39	42
E, 10^3 ksi	...					
E_c, 10^3 ksi	...					
G, 10^3 ksi	...					
μ	...					
Physical Properties:						
ω, lb/in.^{3}	0.324					
C, K, and α	See Figures 6.3.9.0(a),(b), and (c)					

a S-basis. The rounded T_{99} value for F_{tu} (L) = 117 ksi.

Table 6.3.9.0(c). Design Mechanical and Physical Properties of HAYNES®230® Bar

Specification	AMS 5891											
Form	Bar											
Condition	2250 Anneal											
Thickness, in.	≤1.000		1.001 to 2.000		2.001 to 3.000		3.001 to 4.000		4.001 to 5.000		5.001 to 6.000	
Basis	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:												
F_{tu}, ksi: L	110	118	110	117	110	115	110	114	109	112	107	110
F_{ty}, ksi: L	45[a]	51	45[a]	51	45[a]	51	45[a]	51	45[a]	51	45[a]	51
F_{cy}, ksi	...	...	...	...	...	...	...	...	...	...	...	...
F_{su}, ksi	...	...	...	...	...	...	...	...	...	...	...	...
F_{bru}, ksi:												
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...	...	...
F_{bry}, ksi:												
(e/D = 1.5)	...	...	...	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	...	...	...	...	...	...	...	...	...	...	...	...
e, percent: L	35	46	35	46	35	46	35	46	35	46	35	46
E, 10^3 ksi	...											
E_c, 10^3 ksi	...											
G, 10^3 ksi	...											
μ	...											
Physical Properties:												
ω, lb/in.^{3}	0.324											
C, K and α	See Figures 6.3.9.0(a), (b), and (c)											

a S-basis. The rounded T_{99} values for F_{ty} (L) = 48 ksi.

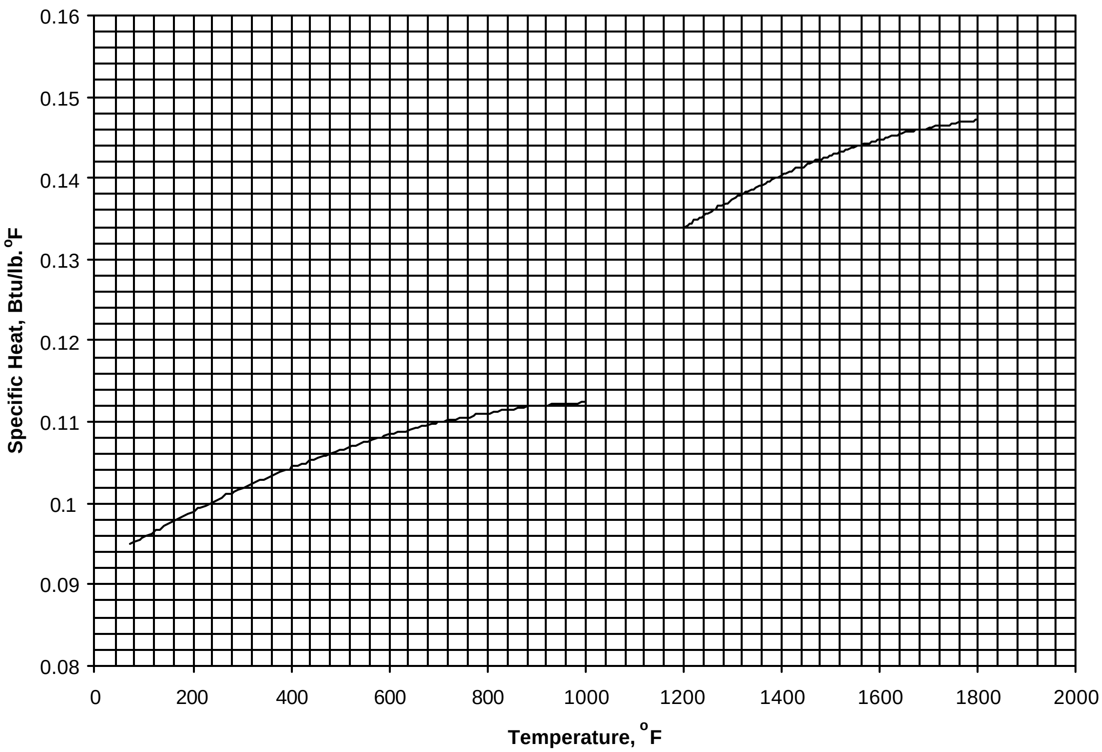

Figure 6.3.9.0(a). Effect of temperature on specific heat of HAYNES® 230® alloy.

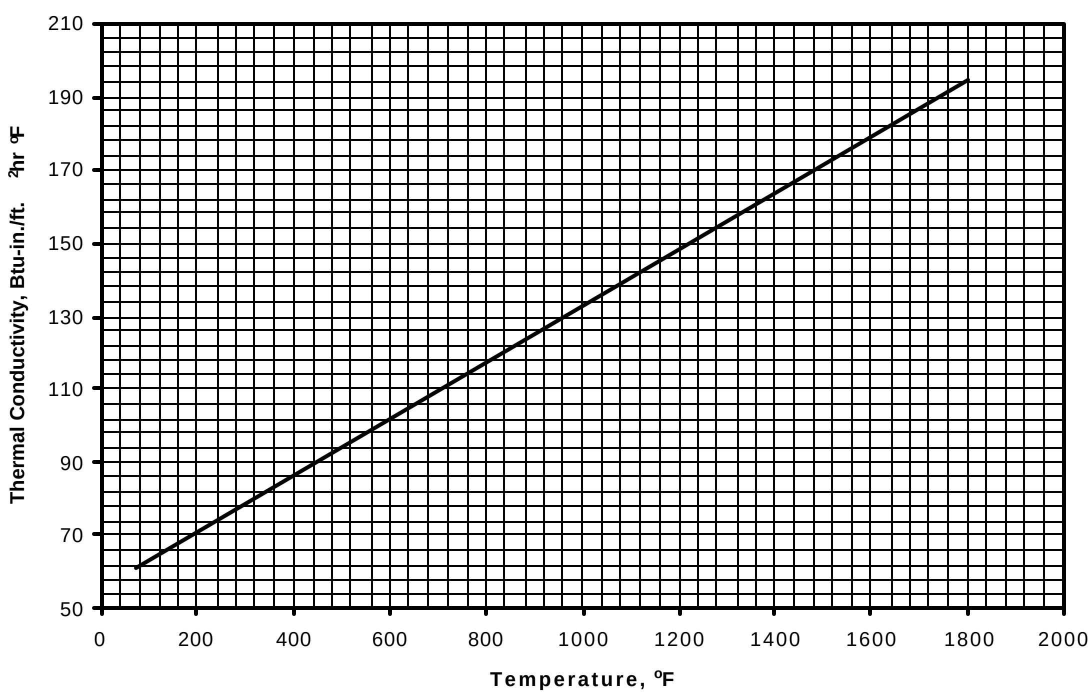

Figure 6.3.9.0(b). Effect of temperature on thermal conductivity of HAYNES® 230® alloy.

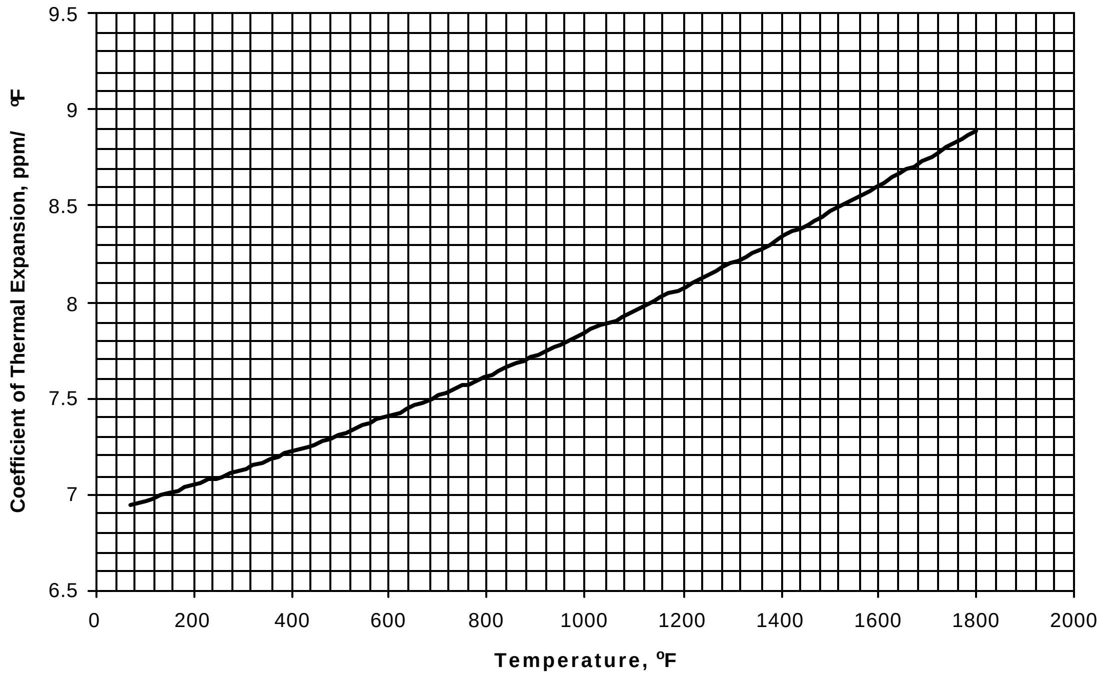

Figure 6.3.9.0(c). Effect of temperature on mean coefficient of thermal expansion of HAYNES® 230® alloy between 70E F and the temperature indicated.

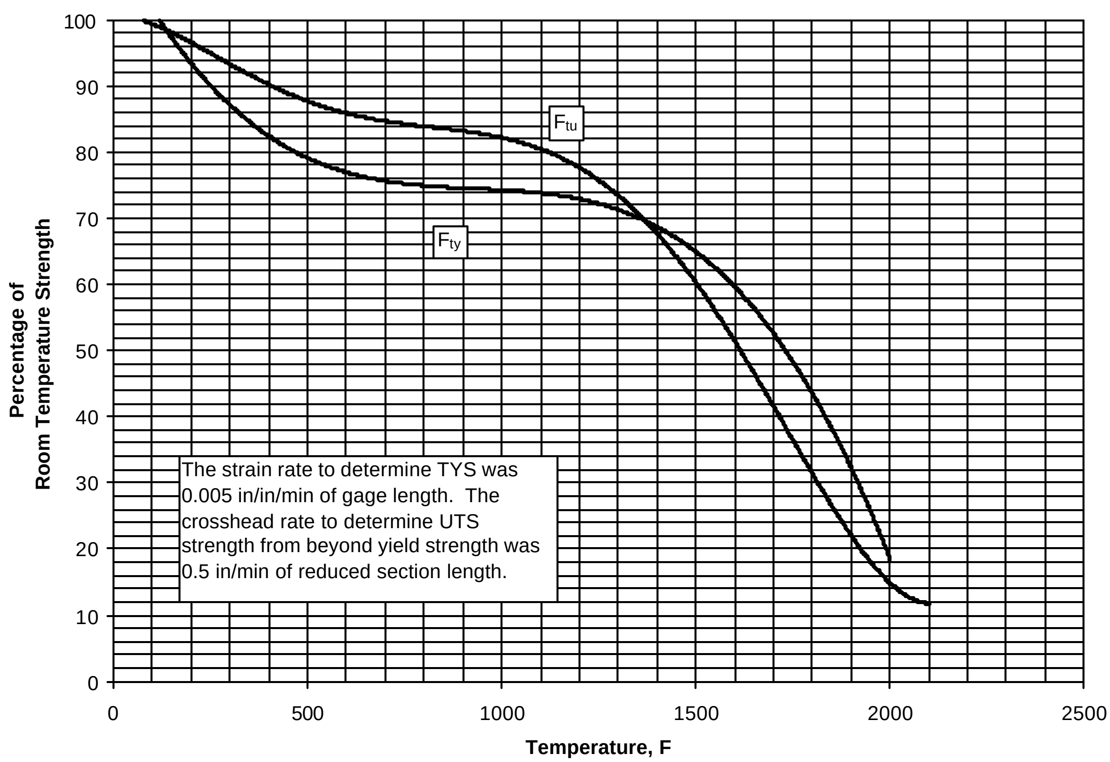

Figure 6.3.9.0(d). Effect of temperature on tensile properties of HAYNES® 230® alloy plate.

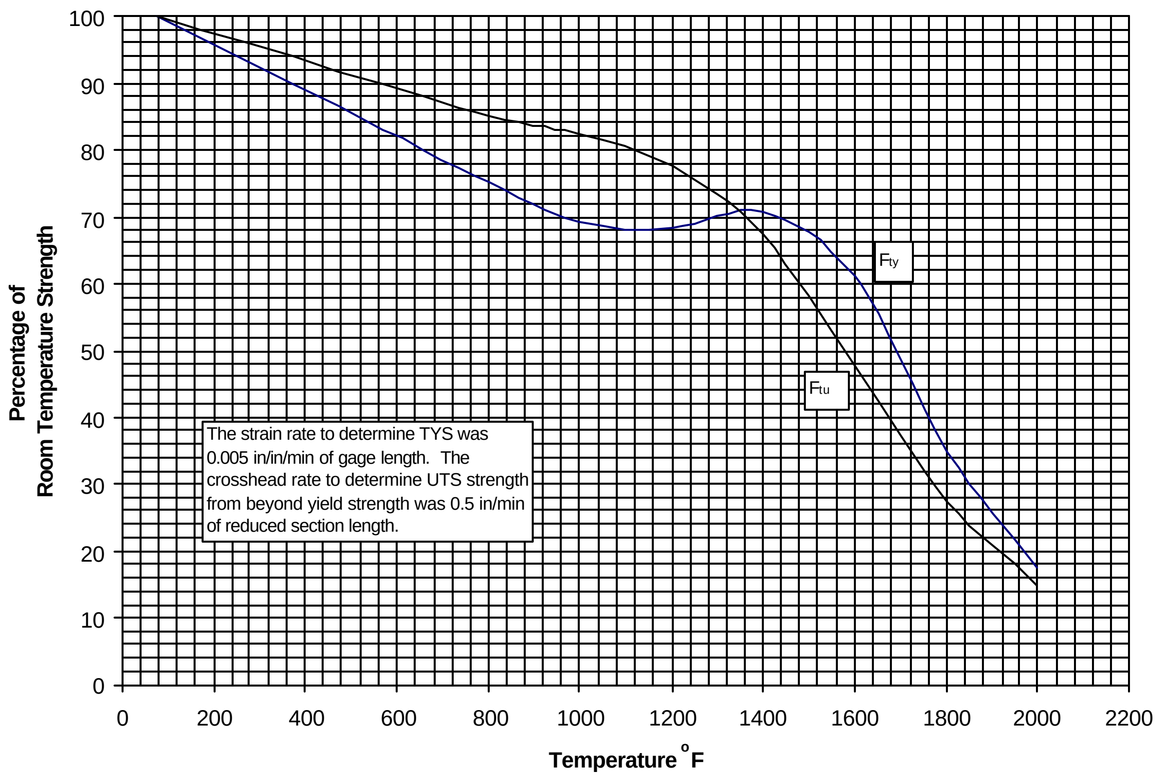

Figure 6.3.9.0(e). Effect of temperature on tensile properties of HAYNES® 230® alloy bar ranging up to 1.3 inches in diameter.

6.4 COBALT-BASE ALLOYS

6.4.0 GENERAL COMMENTS — The use of cobalt in wrought heat-resistant alloys is usually limited to additions of cobalt to alloys of other bases. Very few of the heat-resistant alloys can be considered as cobalt base, since cobalt is seldom the predominating element. For airframe applications, some workability is usually required; the alloys considered in this section are limited to those available in wrought form.

6.4.0.1 *Metallurgical Considerations*

Composition — The common alloying elements for cobalt are chromium, nickel, carbon, molybdenum, and tungsten. Chromium is added to increase strength and oxidation resistance at very high temperatures; nickel to increase toughness; carbon to increase the hardness and strength, especially when combined with chromium and the other carbide formers, molybdenum and tungsten; molybdenum and tungsten also contribute to solid-solution strengthening.

Vacuum melting is not required for these alloys. For this reason, the cobalt-base alloys are often competitively priced with vacuum-melted nickel-base alloys although the price of cobalt is higher than that of nickel.

Heat Treatment — The cobalt-base alloys are heat treated with conventional equipment and fixtures such as those used with austenitic stainless steels. The use of good heat-treating practices is recommended, although this is not so critical as in the case of the nickel-based alloys.

6.4.0.2 *Manufacturing Considerations*

Forging — Because these alloys are designed to have very high strength at temperatures near the forging range, they require the use of heavy forging equipment. However, the forgeability of these alloys is good over a fairly wide range of temperatures. Hot-cold working is neither required nor recommended for these alloys.

Cold Forming — These alloys, when in the solution-treated condition, have excellent ductility and are readily cold formed. Because of their capacity for work hardening, they require higher forming pressures and frequent anneals.

Machining — These alloys are tough and they work harden rapidly; consequently, heavy-duty vibration-free machine tools, sharp cutting tools (high-speed steel or carbide tipped), and low cutting speeds are required.

Welding — The weldability of the cobalt-base alloys is comparable with that of the austenitic stainless steels. Welding may be accomplished by all commonly used welding processes. Large or complex weldments require stress relief.

Brazing — These alloys can be brazed using the same techniques and precautions applicable to stainless steels and nickel-base alloys. Alloys which contain aluminum or titanium require extremely dry, inert gas atmospheres, very high vacuum or a thin (0.002 to 0.0010-inch thick) nickel plating to prevent surface oxidation. It is also necessary to braze the material in the annealed condition and to keep the stresses low during brazing to avoid embrittlement, especially when brazing with low melting alloys.

6.4.0.3 *Special Precautions* — If the cobalt-base alloys have not been exposed to neutron radiation, no special safety precautions in handling are required. However, neutron irradiation creates a very

Correlative Information for Figure 6.4.2.1.8(d)

Product Form/Thickness:
Bar/1.5-inch-thick

Thermal Mechanical Processing History:
Solution treated, water quenched (AMS 5772)

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp., °F
120*	55*		75
		20,353	1800

Stress-Strain Equations:
Cyclic (Companion Specimens)
Proportional Limit = 23 ksi

$$(\Delta\sigma/2) = 66.3\ (\Delta\epsilon_p/2)^{0.12}$$

Specimen Details:
Uniform gage test section
0.250-inch diameter

Reference: 3.8.1.1.8

Test Parameters:
Strain Rate/Frequency - 20 cpm
Wave Form - Triangular
Temperature - 1800°F
Atmosphere - Air

No. of Heats/Lots: 1

Equivalent Strain Equation:
$\text{Log } N_f = 0.047 - 1.317 \log (\Delta\epsilon\text{-}0.00239)$
Standard Deviation in Log(Life) = 0.0126
Adjusted R^2 Statistic = 96%

Sample Size = 15

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

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* Minimum values from AMS 5772.

REFERENCES

6.1.1.1 "Cryogenic Materials Data Handbook," Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, AFML-TDR-64-280, 1970.

6.2.1.1.8 Blatherwick, A. A. and Cers, A., "Fatigue, Creep and Stress-Rupture Properties of Nicrotung, Super A-286, and Inconel 718", AFML-TR-65-4447 (June 1966) (MCIC 65927).

6.3.3.1.8(a) Ruff, P. E., "Effect of Manufacturing Processes on Structural Allowables—Phase II", AFWAL-TR-86-4120, Battelle (November 1986) (MIL-HDBK-5 Source M-656).

6.3.3.1.8(b) Deel, O. L., and Mindlin, H., "Engineering Data on New Aerospace Structural Materials", AFML-TR-71-249, Battelle (December 1971) (MIL-HDBK-5 Source M-465).

6.3.5.1.8(a) Ruff, P. E., "Effect of Manufacturing Processes on Structural Allowables—Phase I," AFWAL-TR-85-4128, Battelle (January 1986) (MIL-HDBK-5 Source M-654).

6.3.5.1.8(b) Korth, G. E. and Smokik, G. R., "Status Report of Physical and Mechanical Test Data of Alloy 718", EG&G Idaho Inc., TREE-1254 (March 1978) (MIL-HDBK-5 Source M-603).

6.3.5.1.9(a) James, L. A., "Heat-to-Heat and/or Melt Practice Variations in Crack Growth Behavior of Inconel 718", Mechanical Properties Test Data for Structural Materials, Quarterly Report for Period Ending October 31, 1977, Report ORNL-5349, pp. 196-199, Oak Ridge National Laboratory (December 1977).

6.3.5.1.9(b) Mills, W. J. and James, L. A., "Effect of Heat-Treatment on Elevated Temperature Fatigue-Crack Growth Behavior of Two Heats of Alloy 718", ASME Paper 78-WA-PVP-3 (December 1978).

6.3.5.1.9(c) James, L. A., "Investigation of Potential Product Form Effects Upon the Fatigue-Crack Growth Behavior of Alloy 718", Mechanical Properties Test Data for Structural Materials, Semiannual Progress Report for Period Ending July 31, 1979, Report ORNL/BRP-79/5, pp. 5.1-5.4, Oak Ridge National Laboratory (October 1979).

6.3.5.1.9(d) James, L. A., "The Effect of Product Form Upon Fatigue-Crack Growth Behavior in Alloy 718", Report HEDL-TME-80-11, Hanford Engineering Development Laboratory (March 1980).

6.3.5.1.9(e) James, L. A. and Mills, W. J., "Effect of Heat-Treatment and Heat-to-Heat Variations in the Fatigue-Crack Growth Response of Alloy 718—Phase I: Macroscopic Variation", Report HEDL-TME-80-9, Hanford Engineering Development Laboratory (March 1980).

6.3.5.1.9(f) James, L. A., "Fatigue-Crack Propagation Behavior of Inconel 718", Report HEDL-TME-75-80, Hanford Engineering Development Laboratory (September 1975).

6.3.5.1.9(g) James, L. A., "Heat-to-Heat and/or Melt Practice Variations in Crack Growth Behavior of Alloy 718", Mechanical Properties Test Data for Structural Materials, Quarterly Progress Report for Period Ending January 31, 1978, Report ORNL-5380, pp. 153-160, Oak Ridge National Laboratory (March 1978).

7.3.2 COPPER BERYLLIUM

7.3.2.0 *Comments and Properties* — Copper beryllium refers to a family of copper-base alloys containing beryllium and cobalt or nickel which cause the alloys to be precipitation hardenable. Data for only one high-strength alloy, designated C17200, which contains 1.90 percent (nominal) beryllium, are presented in this section. This alloy is suitable for parts requiring high strength, good wear, and corrosion resistance. Alloy C17200 is available in the form of rod, bar, shapes, mechanical tubing, strip, and casting.

Manufacturing Considerations — The heat treatable tempers of rod and bar are designated TB00 (AMS 4650) for solution-treated or TD04 (AMS 4651) for solution-treated plus cold worked conditions. After fabrication operations, the material may be strengthened by precipitation heat treatment (aging). Rod and bar are also available from the mill in the TF00 (AMS 4533) and TH04 (AMS 4534) conditions. Mechanical tubing is available from the mill in TF00 (AMS 4535) condition. Machining operations on rod, bar, and tubing are usually performed on material in the TF00 or (TH04) conditions. This eliminates the volumetric shrinkage of 0.02 percent, which occurs during precipitation hardening, as a factor in maintaining final dimensional tolerances. This material has good machinability in all conditions.

Strip is also available in the heat treatable condition. Parts are stamped or formed in a heat treatable temper and subsequently precipitation heat treated. For strip, the heat treatable tempers are designated TB00 (AMS 4530, ASTM B194), TD01 (ASTM B194), TD02 (AMS 4532, ASTM B194), and TD04 (ASTM B194), indicating a progressively greater amount of cold work by the mill. When parts produced from these tempers are precipitation heat treated by the user, the designations become TF00, TH01, TH02, and TH04, respectively. Strip is also available from the mill for the hardened conditions. Design values for these conditions are not included.

Environmental Considerations — The copper beryllium alloys have good corrosion resistance and are not susceptible to hydrogen embrittlement. The maximum service temperature for C17200 copper beryllium products is 500°F for up to 100 hours.

Specifications and Properties — A cross-index to previous and current temper designations for C17200 alloy is presented in Table 7.3.2.0(a).

Table 7.3.2.0(a). Cross-Index to Previous and Current Temper Designations for C17200 Copper Beryllium

Previous Temper	Current ASTM Temper
A	TB00
AT	TF00
¼H	TD01
¼HT	TH01
½H	TD02
½HT	TH02
H	TD04
HT	TH04

Material specifications for alloy C17200 are presented in Table 7.3.2.0(b). Room-temperature mechanical properties are shown in Tables 7.3.2.0(c) through (g). The effect of temperature on physical properties is depicted in Figure 7.3.2.0.

Table 7.3.2.0(b). Material Specifications for C17200 Copper Beryllium Alloy

Specification	Form
ASTM B194	Strip (TB00, TD01, TD02, TD04)
AMS 4530[a]	Strip (TB00)
AMS 4532[a]	Strip (TD02)
AMS 4650	Bar, rod, shapes, and forgings (TB00)
AMS 4533	Bar and rod (TF00)
AMS 4535	Mechanical tubing (TF00)
AMS 4651	Bar and rod (TD04)
AMS 4534	Bar and rod (TH04)

a Noncurrent specification.

The temper index for C17200 alloy is as follows:

Section	Temper
7.3.2.1	TF00
7.3.2.2	TH04

7.3.2.1 ***TF00 Temper*** — Typical tensile and compressive stress-strain and tangent-modulus curves are presented in Figures 7.3.2.1.6(a) and (b).

7.3.2.2 ***TH04 Temper*** — Typical tensile and compressive stress-strain and tangent-modulus curves are presented in Figure 7.3.2.2.6.

Table 7.3.2.0(c). Design Mechanical and Physical Properties of Copper Beryllium Strip

Specification	ASTM B194 AMS 4530[a]	ASTM B194	ASTM B194 AMS 4532[a]	ASTM B194
Form	Strip			
Condition	TF00	TH01	TH02	TH04
Thickness, in.	≤0.188	≤0.188	≤0.188	≤0.188
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	165	175	185	190
LT	...	...	...	...
F_{ty}, ksi:				
L	140	150	160	165
LT	...	...	...	...
F_{cy}[b], ksi: (Estimate)				
L	140	150	160	165
LT	140	150	160	165
F_{su}[b], ksi (Estimate)	90	90	92	95
F_{bru}[b], ksi: (Estimate)				
(e/D = 1.5)	214	227	240	247
(e/D = 2.0)	280	297	314	323
F_{bry}[b], ksi: (Estimate)				
(e/D = 1.5)	196	210	224	231
(e/D = 2.0)	210	225	240	247
e, percent:				
L	3	2.5	1	1
E, 10^3 ksi	18.5			
E_c, 10^3 ksi	...			
G, 10^3 ksi	7.3			
μ	0.27			
Physical Properties:				
ω, lb/in.^{3}	0.298			
C, K, and α	See Figure 7.3.2.0 for TF00 temper			

a Noncurrent specification.
b These properties do not represent values derived from tests, but are estimates.

Table 7.3.2.0(d). Design Mechanical and Physical Properties of C17200 Copper Beryllium Rod and Bar

Specification	AMS 4650 and AMS 4533				
Form	Rod and bar				
Condition	TF00				
Thickness, in.	$\leq$1.500	1.501-2.000	2.001-3.000	3.001-3.500	3.501-4.000
Basis	S	S	S	S	S
Mechanical Properties:					
F_{tu}, ksi:					
L	165	165	165	165	165
ST	...	158	158	158	158
F_{ty}, ksi:					
L	140	140	140	140	140
ST	...	137	137	137	137
F_{cy}, ksi:					
L	150	149	145	143	139
ST	...	142	142	142	142
F_{su}, ksi	...	94	94	94	94
F_{bru}[a], ksi:					
(e/D = 1.5)	226	226	226	226	226
(e/D = 2.0)	290	290	290	290	290
F_{bry}[a], ksi:					
(e/D = 1.5)	200	200	200	200	200
(e/D = 2.0)	225	225	225	225	225
e, percent:					
L	4[b]	4[b]	4[b]	3	3
E, 10^3 ksi	18.5				
E_c, 10^3 ksi	18.7				
G, 10^3 ksi	7.3				
μ	0.27				
Physical Properties:					
ω, lb/in.^{3}	0.298				
C, K, and α	See Figure 7.3.2.0				

a Bearing values are "dry pin" values per Section 1.4.7.1.
b AMS 4650 specifies e = 3 percent.

Table 7.4.1.0(b). Design Mechanical and Physical Properties of MP35N Alloy Bar

Specification	AMS 5845			
Form	Bar			
Condition	Solution treated, cold drawn, and aged			
Diameter, in.[a]	≤0.800		0.801-1.000	1.001-1.750
Basis	A	B	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	260[b]	275	260	260
LT	...	...	...	...
F_{ty}, ksi:				
L	230[c]	266	230	230
LT	...	...	...	...
F_{cy}, ksi:				
L	...	...	...	...
LT	...	...	...	...
F_{su}, ksi	145	147	145	...
F_{bru}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
F_{bry}, ksi:				
(e/D = 1.5)	...	...	...	...
(e/D = 2.0)	...	...	...	...
e, percent (S basis):				
L	8	...	8	8
RA, percent (S basis):				
L	35	...	35	35
E, 10^3 ksi	34.0			
E_c, 10^3 ksi	...			
G, 10^3 ksi	11.7			
μ	...			
Physical Properties:				
ω, lb/in.^{3}	0.304			
C, Btu/(lb)(°F)	0.18 (32 to 70°F)			
K and α	See Figure 7.4.1.0			

a Tensile specimens are located at T/2 location for bars 0.800 inch and under in diameter or distance between parallel sides and at T/4 location of larger size bars. The strength of bar, especially large diameter, may vary significantly from center to surface; consequently, caution should be exercised in machining parts from bars over 0.800 inch in diameter since strengths may be lower than design values depending on depth of material removed from surface.

b The T_{99} value of 266 ksi is higher than specification minimum.

c The T_{99} value of 256 ksi is higher than specification minimum.

Table 7.4.1.0(c). Design Mechanical and Physical Properties of MP35N Alloy Bar

Specification	AMS 5844	
Form	Bar	
Condition	Solution treated and cold drawn	
Diameter, in.[a]	≤1.000	1.001-1.750
Basis	S	S
Mechanical Properties:		
F_{tu}, ksi:		
L	260	260
LT	...	...
F_{ty}, ksi:		
L	230	230
LT	...	...
F_{cy}, ksi:		
L	...	...
LT	...	...
F_{su}, ksi	145	...
F_{bru}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
F_{bry}, ksi:		
(e/D = 1.5)	...	...
(e/D = 2.0)	...	...
e, percent:		
L	8	8
RA, percent:		
L	35	35
E, 10^3 ksi	34.0	
E_c, 10^3 ksi	...	
G, 10^3 ksi	11.7	
μ	...	
Physical Properties:		
ω, lb/in.^{3}	0.304	
C, Btu/(lb)(°F)	0.18 (32 to 70°F)	
K and α	See Figure 7.4.1.0	

a Tensile specimens are located at T/2 location for bars 0.800 inch and under in diameter or distance between parallel sides and at T/4 location for larger size bars. The strength of bar, especially large diameter may vary significantly from center to surface; consequently, caution should be exercised in machining parts from bars over 0.800 inch in diameter since strengths may be lower than design values depending on depth of material removed from surface.

Table 7.5.1.0(b). Design Mechanical and Physical Properties of 2024-T3 Aluminum Alloy, Aramid Fiber Reinforced, Sheet Laminate

Specification	AMS 4254			
Form	Aramid fiber reinforced sheet laminate			
Laminate lay-up	2/1	3/2	4/3	5/4
Nominal thickness, in.	0.032	0.053	0.074	0.094
Basis	S	S	S	S
Mechanical Properties:				
F_{tu}, ksi:				
L	90	96	101	101
LT	48	44	43	42
F_{ty}, ksi:				
L	48	49	49	49
LT	33	30	30	30
F_{cy}, ksi:				
L	35	35	34	33
LT	33	30	30	30
F_{su}[a], ksi	[b]	[b]	[b]	[b]
F_{sy}[a], ksi	16	15	14	14
F_{bru}[c], ksi:				
L (e/D = 1.5)	78	73	73	68
LT (e/D = 1.5)	89	84	80	75
L (e/D = 2.0)	93	86	83	77
LT (e/D = 2.0)	95	89	81	76
F_{bry}[c], ksi:				
L (e/D = 1.5)	53	52	51	50
LT (e/D = 1.5)	56	52	52	52
L (e/D = 2.0)	63	63	61	59
LT (e/D = 2.0)	66	61	61	60
ε_t[d], percent:				
L	2	2	2	2
LT	12	12	12	14
E, 10^3 ksi:				
L	9.9	9.9	9.7	9.6
LT	8.1	7.5	7.1	7.0
E_c, 10^3 ksi:				
L	9.5	9.4	9.3	9.1
LT	8.0	7.5	7.2	7.0
G, 10^3 ksi:				
L	2.7	2.5	2.4	2.2
LT	2.6	2.4	2.4	2.2
μ:				
L	0.33	0.34	0.34	0.32
LT	0.29	0.27	0.26	0.25
Physical Properties:				
ω, lb/in.^{3}	0.086	0.084	0.082	0.081
C, K, and α	...	...	...	...

a Shear values determined from data obtained using Iosipescu shear specimens.
b Shear ultimate strengths not determinable due to excessive deflection of specimen.
c Bearing values are “dry pin” values per Section 1.4.7.1 determined in accordance with ASTM E238.
d Total (elastic plus plastic) strain at failure determined from stress-strain curve.

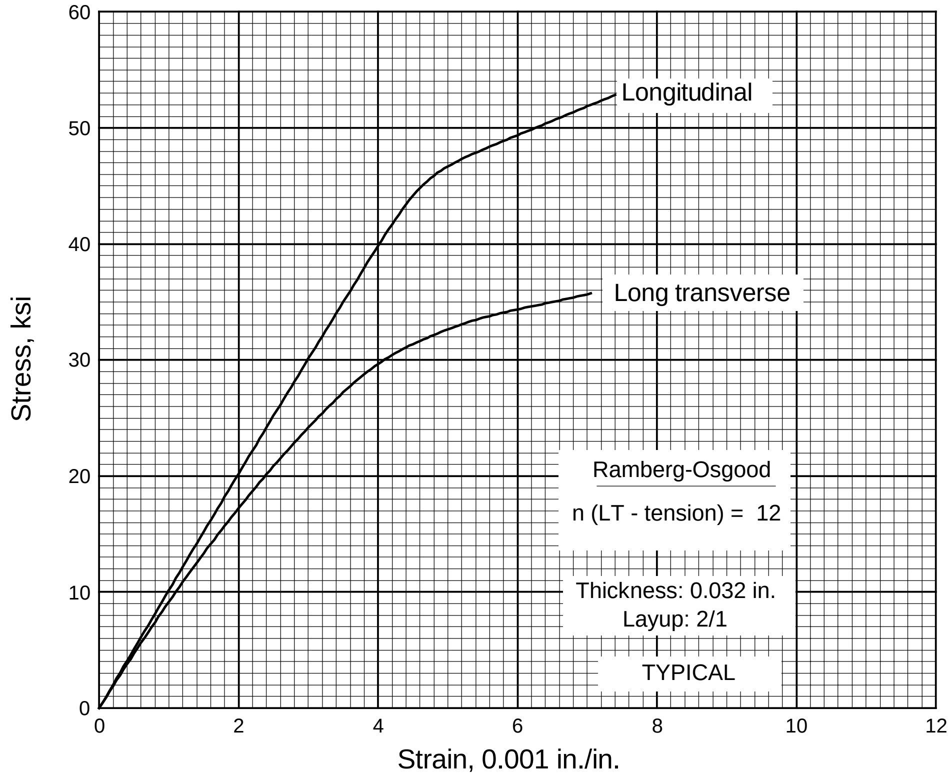

Figure 7.5.1.1.6(a). Typical tensile stress-strain curves for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

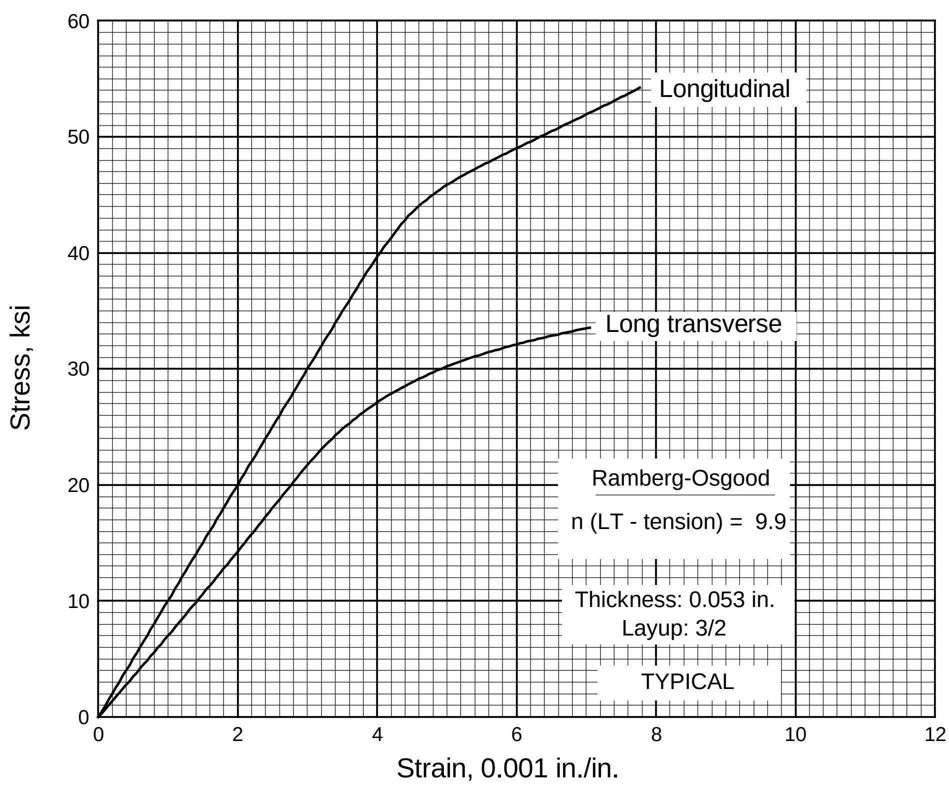

Figure 7.5.1.1.6(b). Typical tensile stress-strain curves for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

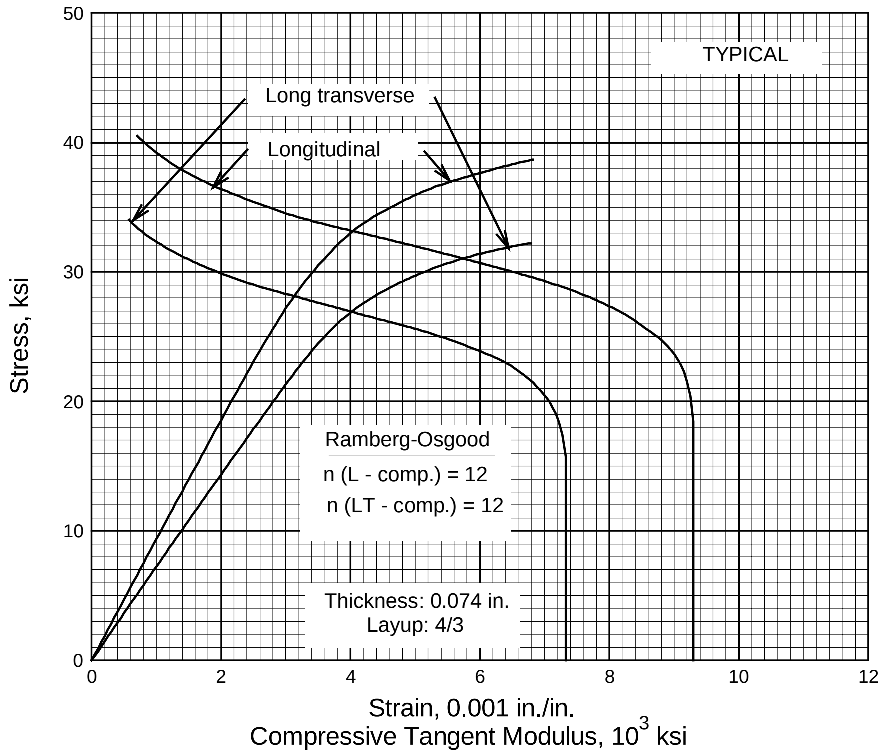

Figure 7.5.1.1.6(g). Typical compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

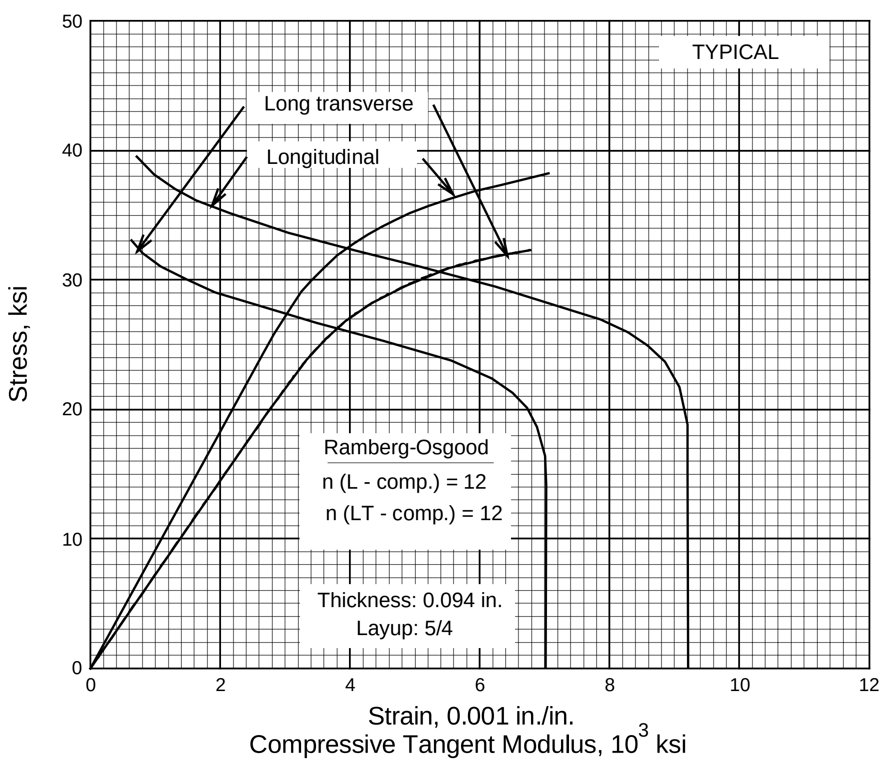

Figure 7.5.1.1.6(h). Typical compressive stress-strain and compressive tangent-modulus curves for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

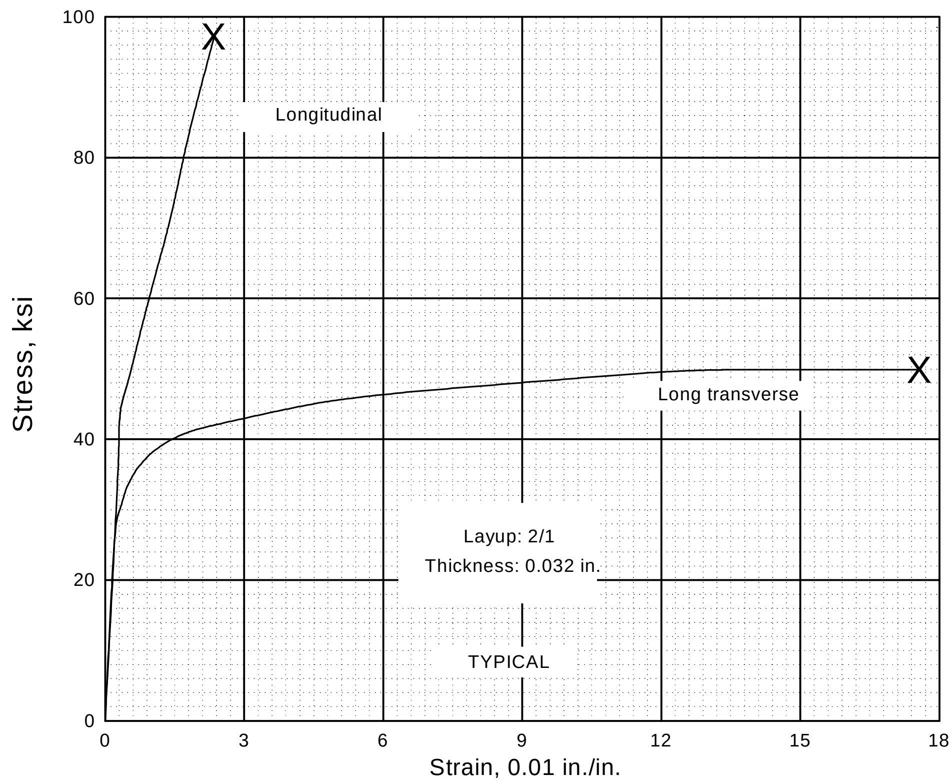

Figure 7.5.1.1.6(i). Typical tensile stress-strain curves (full range) for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

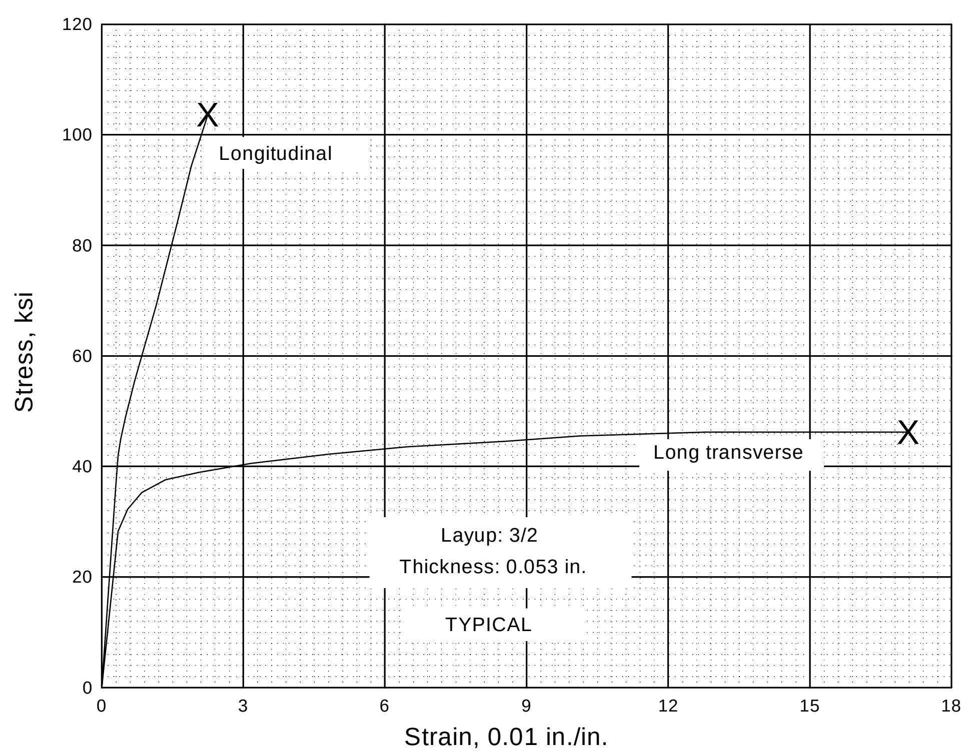

Figure 7.5.1.1.6(j). Typical tensile stress-strain curves (full range) for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

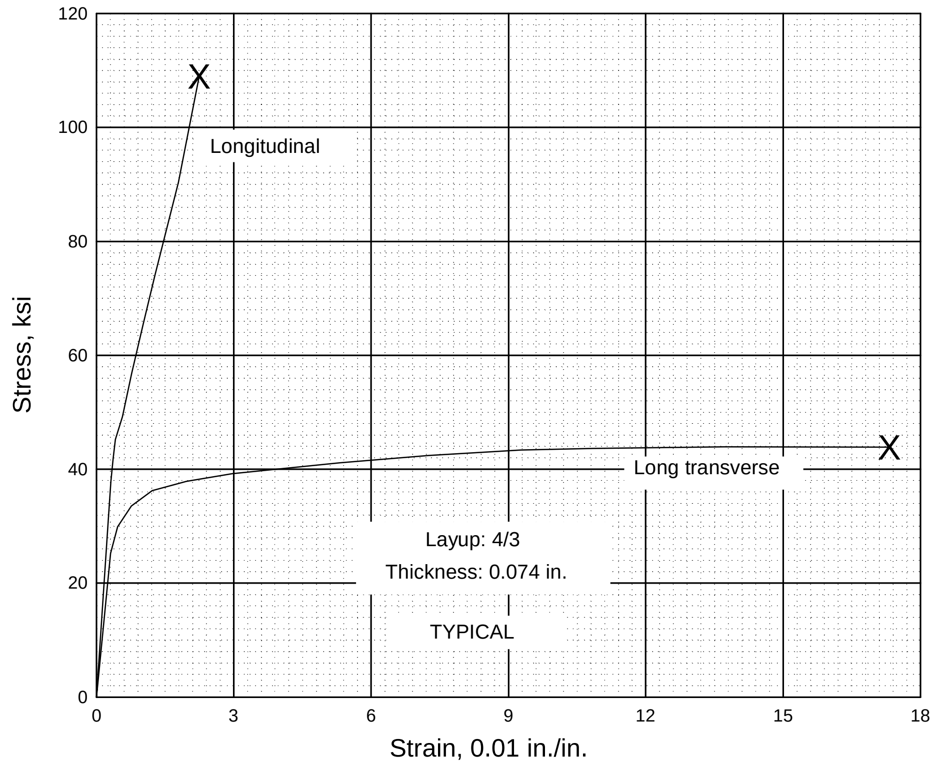

Figure 7.5.1.1.6(k). Typical tensile stress-strain curves (full range) for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

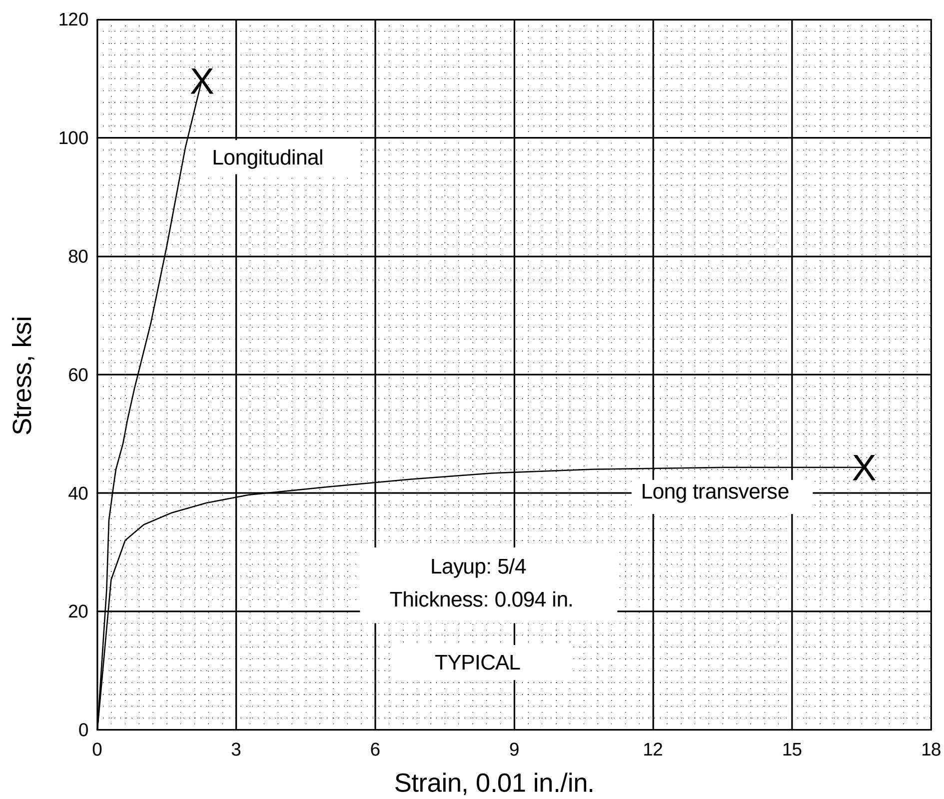

Figure 7.5.1.1.6(l). Typical tensile stress-strain curves (full range) for 2024-T3 aluminum alloy, aramid fiber-reinforced, sheet laminate.

7.5.2 7475-T761 ARAMID FIBER REINFORCED SHEET LAMINATE

7.5.2.0 *Comments and Properties* — This product consists of thin 7475-T761 sheets alternating with aramid fiber layers embedded in a special resin. Nominal thickness of aluminum sheet is 0.012 inch with a prepreg nominal thickness of 0.0085 inch. The primary advantage of this product is the significant improvement in fatigue and fatigue crack growth properties compared to conventional aluminum alloy structures. The product also has good damping capacity and resistance to impact.

Manufacturing Considerations — This product can be fabricated by conventional metal practices for machining, sawing, drilling, joining with fasteners and can be inspected by conventional procedures.

Environmental Considerations — This product has good corrosion resistance. The maximum service temperature is 200°F.

Specifications and Properties — A material specification is presented in Table 7.5.2.0(a). Room-temperature mechanical properties are presented in Table 7.5.2.0(b).

Table 7.5.2.0(a). Material Specifications for 7475-T761 Aramid Fiber Reinforced Sheet Laminate

Specification	Form
AMS 4302	Sheet laminate

7.5.2.1 *T761 Temper* — Tensile and compressive stress-strain and tangent modulus curves are shown in Figures 7.5.2.1.6(a) through (f). Full-range tensile stress-strain curves are presented in Figures 7.5.2.1.6(g) through (j).

Tables 8.1.1(a) through (e) are fastener indexes that list the joint allowables tables for each fastener category. These indexes are provided to make it easier to locate the allowables table for a given fastener and sheet material combination. Each of the indexes generally is similarly structured in the following manner. The left-hand column describes the fastener by referring to the MS or NAS part number or to a vendor part number when the fastener is not covered by either series. The second column contains the table number for the allowables table for each fastener. The fastener column has been so arranged that when protruding head and countersunk head fasteners are included in a given fastener index table, the protruding head tables appear first in the second column. The third column identifies generally the base material of the fastener. Generic terms usually are used, such as steel, aluminum, titanium, etc. The fourth column identifies the specific sheet or plate material.

It is recommended that Section 9.4.1 be reviewed in its entirety since it contains detailed information on the generation and analysis of joint data that results in the joint allowables tables contained in this section.

8.1.1.1 ***Fastener Shear Strengths*** — Fastener shear strengths accepted and documented by the aerospace industry and government agencies are listed in Table 8.1.1.1. Some existing tables in MIL-HDBK-5 may reflect other values; however, new fastener proposals will be classified in accordance with the above-noted table.

8.1.1.2 ***Edge Distance Requirements*** — The joint allowables in MIL-HDBK-5 are based on joint tests having edge distances of twice the nominal hole diameter, 2D. Therefore, the allowables are applicable only to joints having 2D edge distance.

Table 8.1.1(a). Fastener Index for Solid Rivets

Fastener Identification[a]	Table Number	Rivet Material	Sheet Material	Page No.
Rivet Hole Size	8.1.2(a)	...	...	8-10
Shear Strength of Solid Rivets	8.1.2(b)	...	...	8-11
Unit Bearing Strength	8.1.2.1(a)	...	...	8-12
Shear Strength Corection Factors	8.1.2.1(b)	Aluminum	...	8-13
NAS1198 (MC)[b]	8.1.2.1(c)	A-286	A-286	8-14
MS20427M (MC)	8.1.2.2(a)	Monel	AISI 301/302	8-15
MS20427M (D)[b]	8.1.2.2(b)	Monel	AISI 301/302	8-16
MS20426AD (D)	8.1.2.2(c)	Aluminum	Aluminum	8-17
MS20426D (D)	8.1.2.2(d)	Aluminum	Aluminum	8-18
MS20426DD (D)	8.1.2.2(e)	Aluminum	Aluminum	8-19
MS20426 (MC)	8.1.2.2(f)	Aluminum	Clad 2024-T42	8-20
MS20426B (MC)	8.1.2.2(g)	Aluminum	AZ31B-H24	8-21
MS20427M (MC)	8.1.2.2(h)	Monel	Com Pure Titanium	8-22
BRFS-D (MC)	8.1.2.2(i)	Aluminum	Clad 2024-T3	8-23
BRFS-AD (MC)	8.1.2.2(j)	Aluminum	Clad 2024-T3	8-24
BRFS-DD (MC)	8.1.2.2(k)	Aluminum	Clad 2024-T3	8-25
BRFS-T (MC)	8.1.2.2(l)	Ti-45Cb	Clad 7075-T6/Ti-6Al-4V	8-26
MS14218E	8.1.2.2(m)	Aluminum	Clad 2024-T3	8-27
NAS1097E (MC)	8.1.2.2(n)	Aluminum	Clad 2024-T3/7075-T6	8-28
MS14218AD (MC)	8.1.2.2(o)	Aluminum	Clad 2024-T3	8-29
MS14219E (MC)	8.1.2.2(p)	Aluminum	Clad 2024-T3	8-30
MS14219E (MC)	8.1.2.2(q)	Aluminum	Clad 7075-T6	8-31
MS20426E	8.1.2.2(r)	Aluminum	Clad 2024-T3	8-32
MS20426E	8.1.2.2(s)	Aluminum	Clad 7075-T6	8-33
AL905KE (MC)	8.1.2.2(t)	Aluminum	Clad 2024-T3	8-33a

a In some cases, entries in this table identify the subject matter in certain tables.

b MC, machine countersunk holes; D, dimpled holes.

Table 8.1.1(b). Fastener Index for Blind Fasteners

Fastener Identification	Table Number	Fastener Sleeve Material	Sheet or Plate Material	Page No.
		Protruding-head, Friction-Lock Blind Rivets		
CR 6636	8.1.3.1.1(a)	A-286	Various	8-35
MS20600M	8.1.3.1.1(b)	Monel	AISI 301	8-36
MS20600M	8.1.3.1.1(c)	Monel	Clad 2024-T3/7075-T6	8-37
MS20600AD and MS20602AD	8.1.3.1.1(d)	Aluminum	Clad 2024-T3	8-38
MS20600B	8.1.3.1.1(e)	Aluminum	AZ31B-H24	8-39
		Protruding-head, Mechanical-Lock Blind Rivets		
NAS1398C	8.1.3.1.2(a)	A-286	Alloy Steel	8-40
CR 2643	8.1.3.1.2(a)	A-286	Alloy Steel	8-40
NAS1398 MS or MW	8.1.3.1.2(b)	Monel	AISI 301-½ Hard	8-41
NAS1398 MS or MW	8.1.3.1.2(c)	Monel	Clad 7075-T6	8-42
NAS1398B	8.1.3.1.2(d_1)	Aluminum	Clad 2024-T3	8-43
NAS1398D	8.1.3.1.2(d_1)	Aluminum	Clad 2024-T3	8-43
NAS1738B and NAS1738E	8.1.3.1.2(d_2)	Aluminum	Clad 2024-T3	8-44
NAS1398B	8.1.3.1.2(e)	Aluminum	AZ31B-H24	8-45
NAS1738B and NAS1738E	8.1.3.1.2(e)	Aluminum	AZ31B-H24	8-45
CR 2A63	8.1.3.1.2(f)	Aluminum	Clad 2024-T81	8-46
CR 4623	8.1.3.1.2(g)	A-286	Clad 7075-T6	8-47
CR 4523	8.1.3.1.2(h)	Monel	Clad 7075-T6	8-48
NAS1720KE and NAS1720KE (L)	8.1.3.1.2(i)	Aluminum	Clad 7075-T6	8-49
NAS1720C and NAS1720C (L)	8.1.3.1.2(j)	A-286	Clad 2024-T3	8-50
AF3243	8.1.3.1.2(m)	Aluminum	Clad 2024-T3	8-53
HC3213	8.1.3.1.2(n)	Aluminum	Clad 2024-T3	8-54
HC6223	8.1.3.1.2(o)	Aluminum	Clad 2024-T3	8-55
HC6253	8.1.3.1.2(p)	Aluminum	Clad 2024-T3	8-56
AF3213	8.1.3.1.2(q)	Aluminum	Clad 2024-T3	8-56a
CR3213	8.1.3.1.2(r)	Aluminum	Clad 2024-T3	8-56b
CR3243	8.1.3.1.2(s)	Aluminum	Clad 2024-T3	8-56c
HC3243	8.1.3.1.2(t)	Aluminum	Clad 2024-T3	8-56d
AF3223	8.1.3.1.2(u)	Aluminum	Clad 2024-T3	8-56e
CR3223	8.1.3.1.2(v)	Aluminum	Clad 2024-T3	8-56f

Table 8.1.1(b). Fastener Index for Blind Fasteners (Continued)

Fastener Identification	Table Number	Fastener Sleeve Material	Sheet or Plate Material	Page No.
Flush-head, Friction-Lock Blind Rivets				
CR 6626 (MC)[a]	8.1.3.2.1(a)	A-286	Various	8-57
MS20601M (MC)	8.1.3.2.1(b)	Monel	17-7PH (TH1050)	8-58
MS20601M (D)[a]	8.1.3.2.1(c)	Monel	AISI 301	8-59
MS20601M (MC)	8.1.3.2.1(d_1)	Monel	AISI 301-Ann	8-60
MS20601M (MC)	8.1.3.2.1(d_2)	Monel	AISI 301-¼ Hard	8-61
MS20601M (MC)	8.1.3.2.1(d_3)	Monel	AISI 301-½ Hard	8-62
MS20601M (MC)	8.1.3.2.1(e)	Monel	7075-T6	8-63
MS20601AD and MS20603AD (MC)	8.1.3.2.1(f)	Aluminum	Clad 2024-T3	8-64
MS20601B (MC)	8.1.3.2.1(g)	Aluminum	AZ31B-H24	8-65
Flush-head, Mechanical-Lock Spindle Blind Rivets				
NAS1399C (MC)	8.1.3.2.2(a)	A-286	Alloy Steel	8-66
CR 2642 (MC)	8.1.3.2.2(a)	A-286	Alloy Steel	8-66
NAS1399 MS or MW (MC)	8.1.3.2.2(b)	Monel	AISI 301-½ Hard	8-67
NAS1291C (MC)	8.1.3.2.2(c)	A-286	Clad 7075-T6	8-68
NAS1399 MS or MW (MC)	8.1.3.2.2(d)	Monel	Clad 7075-T6	8-69
NAS1921M (MC)	8.1.3.2.2(e)	Monel	Clad 7075-T6	8-70
CR 2A62 (MC)	8.1.3.2.2(f)	Aluminum	Clad 2024-T81	8-71
NAS1921B (MC)	8.1.3.2.2(g)	Aluminum	Clad 7075-T6	8-72
NAS1399B (MC)	8.1.3.2.2(h)	Aluminum	Clad 2024-T3	8-73
NAS1399D (MC)	8.1.3.2.2(h)	Aluminum	Clad 2024-T3	8-73
NAS1739B and NAS1379E (MC)	8.1.3.2.2(i)	Aluminum	Clad 2024-T3	8-74
NAS1739B and NAS1739E (D)	8.1.3.2.2(i)	Aluminum	Clad 2024-T3	8-74
NAS1399B (MC)	8.1.3.2.2(j)	Aluminum	AZ31B-H24	8-75
NAS1739B and NAS1739E (MC)	8.1.3.2.2(j)	Aluminum	AZ31B-H24	8-75
CR 4622 (MC)	8.1.3.2.2(k)	A-286	Clad 7075-T6	8-76
CR 4522 (MC)	8.1.3.2.2(l)	Monel	Clad 7075-T6/T651	8-77
NAS1721KE and NAS1721KE (L) (MC)	8.1.3.2.2(m)	Aluminum	Clad 2024-T3	8-78
NAS1721C and NAS1721C (L) (MC)	8.1.3.2.2(n)	A-286	Clad 7075-T6	8-79
HC3212 (MC)	8.1.3.2.2(q)	Aluminum	Clad 2024-T3	8-82
MBC 4807 and MBC 4907	8.1.3.2.2(r)	Aluminum	Clad 2024-T3	8-83
MBC 4801 and MBC 4901	8.1.3.2.2(s)	Aluminum	Clad 2024-T3	8-84
HC6222	8.1.3.2.2(t)	Aluminum	Clad 2024-T3	8-85
HC6224	8.1.3.2.2(u)	Aluminum	Clad 2024-T3	8-86
HC6252 (MC)	8.1.3.2.2(v)	Aluminum	Clad 2024-T3	8-86a
AF3212 (MC)	8.1.3.2.2(w)	Aluminum	Clad 2024-T3	8-86b
CR3212 (MC)	8.1.3.2.2(x)	Aluminum	Clad 2024-T3	8-86c
AF3242 (MC)	8.1.3.2.2(y)	Aluminum	Clad 2024-T3	8-86d
CR3242 (MC)	8.1.3.2.2(z)	Aluminum	Clad 2024-T3	8-86e
HC3242 (MC)	8.1.3.2.2(aa)	Aluminum	Clad 2024-T3	8-86f
AF3222	8.1.3.2.2(bb)	Aluminum	Clad 2024-T3	8-86g
CR3222	8.1.3.2.2(cc)	Aluminum	Clad 2024-T3	8-86h

a MC, machine countersunk holes; D, dimpled holes.

Table 8.1.1(b). Fastener Index for Blind Fasteners (Continued)

Fastener Identification	Table Number	Fastener Sleeve Material	Sheet or Plate Material	Page No.
		Flush-head Blind Bolts		
MS21140 (MC)	8.1.3.2.3(a)	A-286	Clad 7075-T6/T651	8-87
MS90353 (MC)	8.1.3.2.3(b_1)	Alloy Steel	Clad 2024-T3/T351	8-88
MS90353 (MC)	8.1.3.2.3(b_2)	Alloy Steel	Clad or Bare 7075-T6 or T651	8-89
FF-200, FF-260 and FF-312 (MC)	8.1.3.2.3(c)	Alloy Steel	Clad 2024-T42/ 7075-T6	8-90
NS 100 (MC)	8.1.3.2.3(d)	Alloy Steel	Clad 7075-T6	8-91
SSHFA-200 and SSHFA-260(MC)	8.1.3.2.3(e)	Aluminum	Clad 2024-T42/ 7075-T6	8-92
PLT-150 (MC)	8.1.3.2.3(f)	Alloy Steel	Clad 7075-T6/T651	8-93
NAS1670L (MC)	8.1.3.2.3(g)	Alloy Steel	Clad 7075-T6/T651	8-94
NAS1674L (MC)	8.1.3.2.3(h)	Aluminum	Clad 7075-T6	8-95

a MC, machine countersunk holes; D, dimpled holes.

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8.1.2 SOLID RIVETS — The recommended diameter dimensions of the upset tail on solid rivets shall be at least 1.5 times the nominal shank diameter except for 2024-T4 rivets which shall be at least 1.4 times the nominal shank diameter. Tail heights shall be a minimum of 0.3 diameter. Shear strengths for driven rivets may be based on areas corresponding to the nominal hole diameter provided that the nominal hole diameter is not larger than the values listed in Table 8.1.2(a). If the nominal hole diameter is larger than the listed value, the listed value shall be used. Shear strength values for solid rivets of a number of rivet materials are given in Table 8.1.2(b).

8.1.2.1 Protruding-Head Solid Rivet Joints — The unit load at which shear or bearing type of failure occurs is calculated separately and the lower of the two governs the design.

The design bearing stress for various materials at both room and elevated temperatures is given in the strength properties stated for each alloy or group of alloys and is applicable to riveted joints wherein cylindrical holes are used and where t/D is greater than or equal to 0.18; where t/D is less than 0.18, tests to substantiate yield and ultimate bearing strengths must be performed. These bearing stresses are applicable only for the design of rigid joints where there is no possibility of relative motion of the parts joined without deformation of such parts. Design bearing stresses at low temperatures will be higher than those specified for room temperature; however, no quantitative data are available.

For convenience, "unit" sheet bearing strengths for rivets, based on a bearing stress of 100 ksi and nominal hole diameters, are given in Table 8.1.2.1(a).

In computing protruding-head rivet design shear strengths, the shear strength values obtained from Table 8.1.2(b) should be multiplied by the correction factors given in Table 8.1.2.1(b). This compensates for the reduction in rivet shear strength resulting from high bearing stresses on the rivet at t/D ratios less than 0.33 for single-shear joints and 0.67 for double-shear joints.

For those rivet material sheet material combinations where test data shows the above to be unconservative or for rivet materials other than those shown in Table 8.1.2(b), joint allowables should be established by test in accordance with Section 9.4. From such tests tabular presentation of ultimate load and yield load allowables are made.

Unless otherwise specified, yield load is defined in Section 9.4.1.3.3 as the load which results in a joint permanent set equal to 0.04D, where D is the decimal equivalent of the hole diameter defined in Table 9.4.1.2(a).

Table 8.1.2.1(c) provides ultimate and yield strength data on protruding-head A-286 solid rivets in aged A-286 sheet, for a variety of conditions of exposure.

8.1.2.2 Flush-Head Solid Rivet Joints — Tables 8.1.2.2(a) through (s) contain joint allowables for various flush-head solid rivet/sheet material combinations. The allowable ultimate loads were established from test data using the average ultimate test load divided by a factor of 1.15. (See Section 9.4 for possible variations.) This factor is not applicable to shear strength cutoff values. Shear strength cutoff values may be either the procurement specification shear strength (S value) of the fastener, or if no specification exists, a statistical value determined from test results as described in Section 9.4.

Yield load allowables are established from test data. Unless otherwise specified, the yield load is defined in Section 9.4.1.3.3 as the load which results in a joint permanent set equal to 0.04D, where D is the decimal equivalent of the hole diameter defined in Table 9.4.1.2(a).

For machine countersunk joints, the sheet gage specified in the tables is that of the countersunk sheet. When the noncountersunk sheet is thinner than the countersunk sheet, the bearing allowable for the noncountersunk sheet-fastener combination should be computed, compared to the table value, and the lower of the two values selected. Increased attention should be paid to detail design in cases where t/D < 0.25 because of possibly greater incidence of difficulty in service life.

Table 8.1.2(a). Standard Rivet-Hole Drill Sizes and Nominal Hole Diameters

Rivet Size, in.	1/16	3/32	1/8	5/32	3/16	1/4	5/16	3/8
Drill No.	51	41	30	21	11	F	P	W
Nominal Hole Diameter, in.	0.067	0.096	0.1285	0.159	0.191	0.257	0.323	0.386

Table 8.1.2(b). Single Shear Strength of Solid Rivets[a]

Undriven			Driven			Rivet Size							
Rivet Material	F_{su} (ksi) Min	F_{su} (ksi) Max	Rivet Material	F_{su}^{b} (ksi)	Rivet Designation	1/16	3/32	1/8	5/32	3/16	1/4	5/16	3/8
						Driven Single Shear Strength, lbs[c]							
5056-H32	24	n/a	5056-H321[d]	28[e]	B[f]	99	203	363	556	802	1450	2290	3275
2117-T4	26	n/a	2117-T3	30[e]	AD	106	217	389	596	860	1555	2455	3510
2017-T4	35	42	2017-T3	38[e]	D	134	275	493	755	1085	1970	3115	4445
2024-T4	37	n/a	2024-T31	41[g]	DD	145	297	532	814	1175	2125	3360	4795
7050-T73	41	46	7050-T731[d]	43[e]	E[h]	152	311	558	854	1230	2230	3520	5030
Monel	49	59	Monel	52[e]	M	183	376	674	1030	1490	2695	4260	6085
Ti-45Cb	50	59	Ti-45Cb	53[e]	T	187	384	687	1050	1515	2745	4340	6200
A-286	85	95	A-286	90[e]	-	317	651	1165	1785	2575	4665	7375	10500

a All rivets must be sufficiently driven to fill the rivet hole at the shear plane. Driving changes the rivet strength from the undriven to the driven condition and thus provides the above driven shear strengths.
b Shear stresses are for the as driven condition on B-basis probability.
c Based on nominal hole diameter specified in Table 8.1.2(a).
d The temper designations last digit (1), indicates recognition of strengthening derived from driving.
e The bucktail's minimum diameter is 1.5 times the nominal hole diameter in Table 8.1.2(a).
f Should not be exposed to temperatures over 150°F.
g Driven in the W (fresh or ice box) condition to minimum 1.4D bucktail diameter.
h E (or KE, as per NAS documents).

Table 8.1.2.1(a). Unit Bearing Strength of Sheet on Rivets, F_{br} = 100 ksi

Sheet thickness, in.	Unit Bearing Strength for Indicated Rivet Diameter, lbs							
	1/16	3/32	1/8	5/32	3/16	1/4	5/16	3/8
0.012	80	...	...	...	...	...	...	...
0.016	107	...	...	...	...	...	...	...
0.018	121	173	...	...	...	...	...	...
0.020	134	192	...	...	...	...	...	...
0.025	168	240	321	...	...	...	...	...
0.032	214	307	411	509	...	...	...	...
0.036	241	346	462	572	688	...	...	...
0.040	268	384	514	636	764	...	...	...
0.045	302	432	578	716	860	...	...	...
0.050	335	480	642	795	955	1285	...	...
0.063	422	605	810	1002	1203	1619	2035	...
0.071	476	682	912	1129	1356	1825	2293	2741
0.080	536	768	1028	1272	1528	2056	2584	3088
0.090	603	864	1156	1431	1719	2313	2907	3474
0.100	670	960	1285	1590	1910	2570	3230	3860
0.125	838	1200	1606	1988	2388	3212	4038	4825
0.160	1072	1536	2056	2544	3056	4112	5168	6176
0.190	1273	1824	2442	3021	3629	4883	6137	7334
0.250	1670	2400	3210	3975	4775	6425	8075	9650

Table 8.1.2.1(b). Shear Strength Correction Factors for Solid Protruding Head Rivets[a]

Rivet Diameter, in.	1/16	3/32	1/8	5/32	3/16	1/4	5/16	3/8
	Single-Shear Rivet Strength Factors							
Sheet thickness, in.:								
0.016	0.964	...	...	...	...	...	...	...
0.018	0.981	0.912	...	...	...	...	...	...
0.020	0.995	0.933	...	...	...	...	...	...
0.025	1.000	0.970	0.920	...	...	...	...	...
0.032	...	1.000	0.964	0.925	...	...	...	...
0.036	...	...	0.981	0.946	0.912	...	...	...
0.040	...	...	0.995	0.964	0.933	...	...	...
0.045	...	...	1.000	0.981	0.953	...	...	...
0.050	...	...	...	0.995	0.970	0.920	...	...
0.063	...	...	...	1.000	1.000	0.961	0.922	...
0.071	...	...	...	...	...	0.979	0.944	0.909
0.080	...	...	...	...	...	0.995	0.964	0.933
0.090	...	...	...	...	...	1.000	0.981	0.953
0.100	...	...	...	...	...	...	0.995	0.972
0.125	...	...	...	...	...	...	1.000	1.000
	Double-Shear Rivet Strength Factors							
Sheet thickness, in.:								
0.016	0.687	...	...	...	...	...	...	...
0.018	0.744	0.518	...	...	...	...	...	...
0.020	0.789	0.585	...	...	...	...	...	...
0.025	0.870	0.708	0.545	...	...	...	...	...
0.032	0.941	0.814	0.687	0.560	...	...	...	...
0.036	0.969	0.857	0.744	0.630	0.518	...	...	...
0.040	0.992	0.891	0.789	0.687	0.585	...	...	...
0.045	1.000	0.924	0.834	0.744	0.653	...	...	...
0.050	...	0.951	0.870	0.789	0.708	0.545	...	...
0.063	...	1.000	0.937	0.872	0.808	0.679	0.550	...
0.071	...	...	0.966	0.909	0.852	0.737	0.622	0.508
0.080	...	...	0.992	0.941	0.891	0.789	0.687	0.585
0.090	...	...	1.000	0.969	0.924	0.834	0.744	0.653
0.100	...	...	...	0.992	0.951	0.870	0.789	0.708
0.125	...	...	...	1.000	1.000	0.935	0.870	0.805
0.160	...	...	...	...	...	0.992	0.941	0.891
0.190	...	...	...	...	...	1.000	0.981	0.939
0.250	...	...	...	...	...	...	1.000	1.000

a Sheet thickness is that of the thinnest sheet in single-shear joints and the middle sheet in double-shear joints. Values based on tests of aluminum rivets, Reference 8.1(a).

Table 8.1.2.1(c). Static Joint Strength of Protruding Head A-286 Solid Rivets in A-286 Alloy Sheet at Various Temperatures

Rivet Type	NAS1198 (F_{su} = 90 ksi)								
Sheet Material	A-286, solution treated and aged, F_{tu} = 140 ksi								
Temperature	Room Temperature			1200°F, Stabilized 15 Minutes			1200°F, Rapid Heating in 20 Seconds, Tested in 15 Seconds		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)
Sheet thickness, in.:	Ultimate Strength[a], lbs.								
0.020	478	...	...	331	...	...	470[b]	...	...
0.025	590	740	...	426	626	...	587[b]	726[b]	...
0.032	745	932	1132	560	801	962	752[b]	930[b]	1117[b]
0.040	923	1152	1397	682	1002	1204	783	1164[b]	1397[b]
0.050	1023	1428	1677	...	1044	1505	...	1198	1729[b]
0.063	1131	1578	1821	...	...	1507	...	...	...
0.071	1170	1660	1909	...	...	...	...	...	...
0.080	...	1752	2008	...	...	...	...	...	...
0.090	...	1790	2118	...	...	...	...	...	...
0.100	...	...	2229	...	...	...	...	...	...
0.125	...	...	2504	...	...	...	...	...	...
0.160	...	...	2580	...	...	...	...	...	...
Rivet shear strength[c]	1170	1790	2580	682	1044	1507	783	1198	1729
Sheet thickness, in.:	Yield Strength[a,d], lbs.								
0.020	447	...	...	300	...	...	300	...	...
0.025	590	695	...	374	464	...	374	464	...
0.032	745	932	974	479	593	713	478	593	712
0.040	867	1152	1167	598	741	890	598	740	889
0.050	938	1331	1407	...	925	1112	...	924	1110
0.063	1031	1447	1649	...	...	1400	...	...	...
0.071	1089	1518	1723	...	...	...	...	...	...
0.080	...	1597	1806	...	...	...	...	...	...
0.090	...	1686	1898	...	...	...	...	...	...
0.100	...	...	1990	...	...	...	...	...	...
0.125	...	...	2221	...	...	...	...	...	...
0.160	...	...	2543	...	...	...	...	...	...

a Test data from which the yield and ultimate strengths were derived can be found in Reference 8.1.2.1.
b Yield value is less than 2/3 of indicated ultimate.
c Rivet shear strength is documented in NAS1198 as 90 ksi.
d Permanent set at yield load: 0.005 inch.
Note: Because of difficulties encountered upsetting countersunk head rivets in thin A-286 sheet, such conditions should be avoided in design.

Table 8.1.2.2(o). Static Joint Strength of 120° Flush Shear Head Aluminum Alloy (2117-T3) Solid Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	MS14218AD[a] (F_{su} = 30 ksi)					
Sheet Material	Clad 2024-T3					
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	3/32 (0.096)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	7/32 (0.228)	1/4 (0.257)
	Ultimate Strength, lbs					
Sheet thickness, in.:						
0.020	125[c]	...	...	...	...	...
0.025	153	212[c]	...	...	...	...
0.032	188	263	334[c]	...	...	...
0.040	216	322	408	498[c]	...	...
0.050	217	380	498	609	740[c]	849[c]
0.063	...	388	588	751	910	1040
0.071	...	...	596	817	1015	1155
0.080	...	...	...	842	1125	1290
0.090	...	...	...	862	1205	1425
0.100	...	...	...	...	1225	1520
0.125	...	...	...	...	...	1555
Rivet shear strength[d]	217	388	596	862	1225	1555
	Yield Strength[e], lbs					
Sheet thickness, in.:						
0.020	125	...	...	...	...	...
0.025	153	212	...	...	...	...
0.032	188	263	334	...	...	...
0.040	216	319	408	498	...	...
0.050	217	370	492	609	740	849
0.063	...	388	574	733	910	1040
0.071	...	...	596	794	1005	1155
0.080	...	...	...	842	1090	1275
0.090	...	...	...	862	1180	1380
0.100	...	...	...	...	1225	1480
0.125	...	...	...	...	...	1555
Head height (ref.), in.	0.022	0.027	0.035	0.044	0.053	0.061

a Data supplied by Briles Rivet Corp.
b Load allowables developed from tests with hole diameters noted, except 3/32, 5/32, and 3/16 diameters were 0.098, 0.161, and 0.1935, respectively. Hole tolerance was +0.0005-0.001 inch.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
d Shear strength based on Table 8.1.2(b) and F_{su} = 30 ksi.
e Permanent set at yield load: 4% of nominal hole diameter (Ref. 9.4.1.3.3).

Table 8.1.2.2(p). Static Joint Strength of 120° Flush Tension Type Head Aluminum Alloy (7050-T731) Solid Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	MS14219 E[a] (F_{su} = 43 ksi)							
Sheet Material	Clad 2024-T3							
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	3/32 (0.096)	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	7/32 (0.228)	1/4 (0.257)	9/32 (0.290)	5/16 (0.523)
	Ultimate Strength, lbs							
Sheet thickness, in.:								
0.032	210	...	...	...	...	...	...	...
0.040	279	[c] 339	...	...	...	...	...	...
0.050	310	473	[c] 527	...	...	...	...	...
0.063	311	538	743	[c] 819	...	...	...	...
0.071	...	558	788	979	[c] 1065	...	...	...
0.080	...	...	834	1105	1280	[c] ...	...	...
0.090	...	...	854	1165	1520	1625	...	...
0.100	...	...	...	1230	1605	1890	[c] 2020	2120 [c]
0.125	...	...	...	...	1755	2145	2580	2965
0.160	...	...	...	...	...	2230	2840	3415
0.190	...	...	...	...	...	...	...	3525
Rivet shear strength[d]	311	588	854	1230	1755	2230	2840	3525
	Yield Strength[e], lbs							
Sheet thickness, in.:								
0.032	210	...	...	...	...	...	...	...
0.040	277	339	...	...	...	...	...	...
0.050	301	468	527	...	...	...	...	...
0.063	309	538	728	819	...	...	...	...
0.071	...	543	788	979	1065	...	...	...
0.080	...	...	823	1100	1280	...	...	...
0.090	...	...	833	1165	1490	1625	...	...
0.100	...	...	...	1190	1605	1875	2020	2120
0.125	...	...	...	...	1705	2145	2580	2945
0.160	...	...	...	...	...	2200	2765	3390
0.190	...	...	...	...	...	...	...	3455
Head height (ref.), in.	0.034	0.041	0.053	0.068	0.077	0.090	0.100	0.104

a Data supplied by Briles Rivet Corp.
b Load allowables developed from tests with hole diameters noted, except 5/32, 3/16, and 5/16 diameter were 0.161, 0.1935, and 0.316, respectively. Hole tolerances were + 0.0005, -0.001 inch.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
d Rivet shear strength based on Table 8.1.2(b) and F_{su} = 43 ksi.
e Permanent set at yield load: 4% of nominal hole diameter (Ref. 9.4.1.3.3).

Table 8.1.2.2 (s). Static Joint Strength of Solid 100° Flush Head Alumunim Alloy (7050-T73) Solid Rivets in Machine Countersunk Aluminum Alloy Sheet

Rivet Type	MS20426E (F_{su} = 41 ksi)[a]			
Sheet Material	Clad 7075-T6			
Rivet Diameter, in.	1/8	5/32	3/16	1/4
(Nominal Hole Diameter, in.)[b]	(0.1285)	(0.159)	(0.191)	(0.257)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.040	318	...	...	...
0.050	393	[c] 492	...	...
0.063	440	606	[c] 745	...
0.071	469	642	840	[c] ...
0.080	502	683	898	...
0.090	531	728	952	1430 [c]
0.100	...	773	1005	1570
0.125	...	814	1140	1755
0.160	...	...	1175	2010
0.190	...	...	...	2125
Rivet shear strength[d]	531	814	1175	2125
	Yield Strength[e], lbs			
Sheet thickness, in.:				
0.040	257	...	...	...
0.050	330	399	...	...
0.063	423	515	607	...
0.071	469	586	693	...
0.080	502	666	789	...
0.090	531	728	896	1175
0.100	...	773	1005	1320
0.125	...	814	1140	1680
0.160	...	...	1175	2010
0.190	...	...	...	2125
Head Height (ref.), in.	0.042	0.055	0.070	0.095

a Data supplied by Lockheed Ga. Co., Air Force Materials Laboratory, Allfast, Cherry Fasteners, Douglas Aircraft Co., and Huck Mfg. Co.
b Load allowables developed from tests with hole diameters of 0.130, 0.158, 0.191, and 0.256 ± 0.003 inch.
c The values in the table above the horizontal line in each column are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires the specific approval of the procuring agency.
d Shear strength based on area computed from nominal hole diameters in Table 8.1.2(b) and F_{su} = 41 ksi.
e Permanent set at yield load: 4% of the nominal hole diameter.

Table 8.1.2.2(t). Static Joint Strength of 105 degree Flush Shear Head Aluminum Alloy (7050) Solid Rivet in 100 degree Machine-Countersunk Alloy Sheet

Rivet Type	AL 905 KE[a] (F_{su} = 41 ksi)			
Sheet Material	Clad 2024-T3			
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	1/4 (0.257)
	Ultimate Strength, lbs.			
Sheet Thickness, in.:				
0.032	325[c]	---	---	---
0.040	396	502[c]	---	---
0.050	452	612	750[c]	---
0.063	498	696	923	1280[c]
0.071	526	731	980	1425
0.080	531	771	1030	1585
0.090	---	814	1080	1735
0.125	---	---	1175	1985
0.160	---	---	---	2125
Rivet Shear Strength[d]	531	814	1175	2125
	Yield Strength, lbs[e]			
Sheet Thickness, in.:				
0.032	268	---	---	---
0.040	326	415	---	---
0.050	399	504	619	---
0.063	493	620	759	1060
0.071	526	692	845	1175
0.080	531	771	942	1305
0.090	---	814	1050	1450
0.125	---	---	1175	1955
0.160	---	---	---	2125
Head Height [ref.],[f] in.	0.029	0.037	0.046	0.060

a Data supplied by Ateliers De La Haute Garonne SARL.
b Loads developed from tests with hole diameters of 0.1285, 0.161, 0.193, and 0.257, +/- 0.001 inch.
c The values above the horizontal line in each column are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring activity.
d Rivet shear strength is based upon Table 8.1.2(b) and F_{su} = 41 ksi.
e Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).
f Head height values reflect driven rivet configuration.

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8.1.3 Blind Fasteners — The strengths shown in the following tables are applicable only for the grip lengths and hole tolerances recommended by the respective fastener manufacturers. For some fastener systems, permanent set at yield load may be increased if hole sizes greater than those listed in the applicable table are used. This condition may exist even though the test hole size lies within the manufacturer's recommended hole size range (Reference 9.4.1.3.3).

The strength values were established from test data and are applicable to "joints" with $e/D \geq 2.0$. For joints with e/D ratios less than 2.0, tests to substantiate the use of yield and ultimate strength allowables must be made. Ultimate strength values of protruding- and flush-head blind fasteners were obtained as described in Section 9.4. The analyses included dividing the average ultimate load from test data by 1.15. This factor is not applicable to shear strength cutoff values which may be either the procurement specification shear strength (S values) of the fastener, or if no specification exists, a statistical value determined from test results as described in Section 9.4.

Unless otherwise specified, yield load is defined in Section 9.4.1.3.3 as the load which results in a joint permanent set equal to 0.04D, where D is the decimal equivalent of the hole or fastener shank diameter, as defined in Table 9.4.1.2(a). Some tables are footnoted to show the previous criteria used for those particular tables.

For machine countersunk joints, the sheet gage specified in the tables is that of the countersunk sheet. When the noncountersunk sheet is thinner than the countersunk sheet, the bearing allowable for the noncountersunk sheet-fastener combination should be computed, compared to the table value, and the lower of the two values selected. Increased attention should be paid to detail design in cases where $t/D < 0.25$ because of the possibility of unsatisfactory service life.

Joint allowable strengths of blind fasteners in double-dimpled or dimpled into machine countersunk applications should be established on the basis of specific tests acceptable to the procuring or certifying agency. In the absence of such data, allowables for blind fasteners in machine countersunk sheet may be used.

Reference should be made to the requirements of the applicable procuring or certifying agency relative to the use of blind fasteners such as the limitations of usage in design standard MS33522.

8.1.3.1 *Protruding-Head Blind Fasteners*

8.1.3.1.1 *Friction-Lock Blind Rivets* — Tables 8.1.3.1.1(a) through 8.1.3.1.1(e) contain joint allowables for various protruding-head, friction-lock blind rivet/sheet material combinations.

8.1.3.1.2 *Mechanical-Lock Spindle Blind Rivets* — Tables 8.1.3.1.2(a) through (p) contain joint allowables for various protruding-head, mechanical-lock spindle blind rivet/sheet material combinations.

8.1.3.2 *Flush-Head Blind Fasteners*

8.1.3.2.1 *Friction-Lock Blind Rivets* — Tables 8.1.3.2.1(a) through (g) contain joint allowables for various flush-head, friction-lock blind rivet/sheet material combinations.

8.1.3.2.2 *Mechanical-Lock Spindle Blind Rivets* — Tables 8.1.3.2.2(a) through (u) contain joint allowables for various flush-head, mechanical-lock spindle blind rivet/sheet material combinations.

8.1.3.2.3 *Flush-Head Blind Bolts* — Tables 8.1.3.2.3(a) through (h) contain joint allowables for various flush-head blind bolt/sheet material combinations.

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Table 8.1.3.1.2(m). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	AF3243 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.		
Sheet Thickness, in.:			
0.025	242	---	---
0.032	302	382	453
0.040	371	467	551
0.050	456	572	674
0.063	538	710	834
0.071	556	795	932
0.080	577	828	1040
0.090	600	856	1110
0.100	622	885	1140
0.125	679	955	1225
0.160	759	---	1335
Rivet Shear Strength[c]	814	1245	1685
	Yield Strength, lbs[d]		
Sheet Thickness, in.:			
0.025	242	---	---
0.032	302	382	453
0.040	371	467	551
0.050	456	572	674
0.063	538	710	834
0.071	556	795	932
0.080	577	828	1040
0.090	600	856	1110
0.100	622	885	1140
0.125	679	955	1225
0.160	759	---	1335

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

a Data supplied by Allfast Fastening Systems Inc.
b Loads developed from tests with hole diameters of 0.144, 0.178, and 0.207, +/-0.001 inch.
c Rivet shear strength is documented on AF3243 standards drawing.
d Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.1.2(n). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	HC3213 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet Thickness, in.:			
0.020	225	---	---
0.025	265	351	---
0.032	320	419	527
0.040	383	498	621
0.050	461	596	738
0.063	538	723	891
0.071	558	801	985
0.080	581	840	1090
0.090	607	872	1180
0.100	632	904	1220
0.125	664	983	1315
0.160	---	1030	1445
0.190	---	---	1480
Rivet Shear Strength[c]	664	1030	1480
	Yield Strength, lbs[d]		
Sheet Thickness, in.:			
0.020	182	---	---
0.025	222	284	---
0.032	278	354	431
0.040	343	434	527
0.050	423	534	647
0.063	436	658	803
0.071	444	668	898
0.080	453	679	951
0.090	463	691	965
0.100	473	704	980
0.125	497	734	1015
0.160	---	777	1065
0.190	---	---	1110

a Data supplied by Huck International Inc.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.
c Rivet shear strength is documented on HC3213 standards drawing.
d Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.1.2(o). Static Joint Strength of Protruding Head Locked Spindle Aluminum Alloy Blind Rivets in Aluminum Alloy Sheet

Rivet Type	HC6223[a] (F_{su} = 50 ksi) Nominal		
Sheet and Plate Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs		
Sheet thickness, in.:			
0.016	...	...	...
0.020	...	...	...
0.025	272	...	...
0.032	367	437	...
0.040	427	573	661
0.050	476	664	864
0.063	539	743	975
0.071	578	792	1033
0.080	622	846	1099
0.090	664	907	1171
0.100	...	967	1244
0.125	...	1030	1425
0.160	...	...	1480
0.190	...	...	...
Rivet shear strength[b]	664	1030	1480
	Yield Strength[c], lbs		
Sheet thickness, in.:			
0.016	...	...	...
0.020	...	...	...
0.025	255	...	...
0.032	320	406	...
0.040	394	498	605
0.050	417	613	743
0.063	437	648	901
0.071	449	664	920
0.080	463	681	940
0.090	478	700	963
0.100	...	720	986
0.125	...	768	1044
0.160	...	...	1125
0.190	...	...	...

a Data supplied by Huck International, Inc.
b Rivet shear strength is documented in MIL-R-7885D.
c Permanent set at yield load: 4% of nominal hole diameter (see 9.4.1.3.3).

Table 8.1.3.1.2(p). Static Joint Strength of Protruding Head Locked Spindle Aluminum Alloy Blind Rivets in Aluminum Alloy Sheet

Rivet Type	HC6253[a] (F_{su} = 50 ksi)		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs		
Sheet thickness, in.:			
0.016	...	...	...
0.020	...	...	...
0.025	...	...	...
0.032	344	419	...
0.040	436	532	613
0.050	513	674	777
0.063	559	789	992
0.071	588	824	1055
0.080	620	864	1101
0.090	656	908	1152
0.100	691	952	1204
0.125	781	1063	1332
0.160	814	1217	1512
0.190	...	1245	1666
0.250	...	...	1685
Rivet shear strength[b]	814	1245	1685
	Yield Strength[c], lbs		
Sheet thickness, in.:			
0.016	...	...	...
0.020	...	...	...
0.025	...	...	...
0.032	344[d]	419[d]	...
0.040	403	532[d]	613[d]
0.050	462	619	731
0.063	523	715	879
0.071	541	774	948
0.080	560	805	1025
0.090	583	832	1079
0.100	605	859	1110
0.125	660	928	1190
0.160	738	1024	1302
0.190	...	1245	1397
0.250	...	...	1588

a Data supplied by Huck International, Inc.
b Rivet shear strength is documented in MIL-R-7885D.
c Permanent set at yield load: 4% of nominal hole diameter (see 9.4.1.3.3).
d Yield reduced to match ultimate strength.

Table 8.1.3.1.2(q). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	AF3213 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet Thickness, in.:			
0.020	223	---	---
0.025	262	347	---
0.032	317	416	522
0.040	380	494	616
0.050	411	592	733
0.063	441	640	875
0.071	459	663	902
0.080	480	689	933
0.090	503	717	968
0.100	526	746	1000
0.125	583	818	1085
0.160	---	918	1205
0.190	---	---	1310
Rivet Shear Strength[c]	664	1030	1480
	Yield Strength, lbs[d]		
Sheet Thickness, in.:			
0.020	223	---	---
0.025	262	347	---
0.032	317	416	522
0.040	362	494	616
0.050	378	562	733
0.063	398	588	814
0.071	411	604	833
0.080	425	622	854
0.090	441	641	878
0.100	457	661	901
0.125	496	710	960
0.160	---	779	1040
0.190	---	---	1110

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

a Data supplied by Allfast Fastening Systems Inc.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.
c Rivet shear strength is documented on AF3213 standards drawing.
d Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.1.2(r). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	CR3213 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet Thickness, in.:			
0.020	250	---	---
0.025	280	389	---
0.032	322	441	576
0.040	370	501	648
0.050	430	576	737
0.063	492	673	853
0.071	513	733	925
0.080	536	769	1005
0.090	562	801	1080
0.100	587	833	1115
0.125	652	913	1215
Rivet Shear Strength[c]	664	1030	1480
	Yield Strength, lbs[d]		
Sheet Thickness, in.:			
0.020	214	---	---
0.025	238	332	---
0.032	272	375	491
0.040	298	424	550
0.050	315	463	623
0.063	338	491	672
0.071	351	508	692
0.080	367	527	716
0.090	384	549	741
0.100	401	570	767
0.125	445	624	831

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

a Data supplied by Textron Aerospace Fasteners.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.
c Rivet shear strength is documented on CR3213 standards drawing.
d Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.1.2(s). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	CR3243 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.		
Sheet Thickness, in.:			
0.025	317	---	---
0.032	366	494	617
0.040	421	562	696
0.050	489	647	795
0.063	579	758	924
0.071	623	826	1000
0.080	640	902	1090
0.090	660	957	1190
0.100	679	981	1280
0.125	728	1040	1350
Rivet Shear Strength[c]	814	1245	1685
	Yield Strength, lbs[d]		
Sheet Thickness, in.:			
0.025	272	---	---
0.032	317	425	527
0.040	368	488	600
0.050	432	567	692
0.063	451	664	811
0.071	462	677	884
0.080	475	693	911
0.090	489	710	931
0.100	503	728	951
0.125	538	771	1000

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

a Data supplied by Textron Aerospace Fasteners.
b Loads developed from tests with hole diameters of 0.144, 0.178, and 0.207, +/-0.001 inch.
c Rivet shear strength is documented on CR3243 standards drawing.
d Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.1.2(t). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	HC3243 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.		
Sheet Thickness, in.:			
0.025	252	---	---
0.032	312	397	473
0.040	380	481	571
0.050	465	586	693
0.063	546	723	852
0.071	576	803	950
0.080	610	844	1060
0.090	647	891	1125
0.100	685	937	1175
0.125	779	1050	1310
0.160	814	1215	1500
0.190	---	1245	1665
0.250	---	---	1685
Rivet Shear Strength[c]	814	1245	1685
	Yield Strength, lbs[d]		
Sheet Thickness, in.:			
0.025	252	---	---
0.032	312	397	473
0.040	371	481	571
0.050	401	569	693
0.063	440	617	790
0.071	464	646	824
0.080	491	680	863
0.090	521	717	906
0.100	551	754	949
0.125	626	846	1055
0.160	730	976	1205
0.190	---	1085	1335
0.250	---	---	1595

a Data supplied by Huck International Inc.
b Loads developed from tests with hole diameters of 0.144, 0.178, and 0.207, +/-0.001 inch.
c Rivet shear strength is documented on HC3243 standards drawing.
d Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.1.2(u). Static Joint Strength of Blind Protruding Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	AF3223 (F_{su} = 50 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.025	272	...	...
0.032	331	431	...
0.040	390	516	640
0.050	421	606	767
0.063	461	656	883
0.071	486	687	920
0.080	514	722	962
0.090	545	760	1005
0.100	576	799	1050
0.125	653	896	1170
0.160	664	1030	1330
0.190	...	...	1460
Rivet shear strength[c]	664	1030	1460
	Yield Strength[d], lbs.		
Sheet thickness, in.:			
0.025	243	...	...
0.032	312	387	...
0.040	390	485	580
0.050	421	606	727
0.063	448	656	883
0.071	463	678	920
0.080	481	700	958
0.090	500	723	987
0.100	519	747	1015
0.125	566	806	1085
0.160	633	889	1185
0.190	...	...	1270

a Data supplied by Allfast Fastening Systems Inc.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.
c Rivet shear strength as documented in Allfast Fastening Systems Inc P-127.
d Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.1.2(v). Static Joint Strength of Protruding Head 5056 Aluminum Alloy Rivets in Clad Aluminum Alloy Sheet

Rivet Type	CR3223 (F_{su} = 50 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.025	257	...	...
0.032	316	408	...
0.040	383	492	606
0.050	450	596	731
0.063	486	701	894
0.071	509	729	987
0.080	534	760	1025
0.090	562	795	1065
0.100	590	830	1105
0.125	659[c]	917	1210
0.160	664[c]	1030[c]	1355[c]
0.190	...	...	1480[c]
Rivet shear strength[d]	664	1030	1480
	Yield Strength[e], lbs.		
Sheet thickness, in.:			
0.025	221	...	...
0.032	279	351	...
0.040	321	434	525
0.050	333	498	649
0.063	350	519	720
0.071	360	531	736
0.080	371	545	752
0.090	384	561	771
0.100	396	577	790
0.125	428	616	837
0.160	472	671	903
0.190	...	...	959

a Data supplied by Textron Aerospace Fasteners.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.0005 inch.
c Yield value is less than 2/3 of indicated ultimate strength value.
d Rivet shear strength as documented in Textron Aerospace Fasteners PS-CMR-3000.
e Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.2.1(e). Static Joint Strength of Blind 100° Flush-Head Monel Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	MS20601M (F_{su} = 55 ksi)			
Sheet Material	7075-T6			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.040	320[a]	b ...	...	...
0.050	393	494[a]	b ...	...
0.063	487	612[a]	747[a]	b ...
0.071	545	684	832[a]	...
0.080	565	766	930[a]	...
0.090	587	840	1040	1425[a] b
0.100	610	867	1150	1570[a]
0.125	...	937	1270	1940
0.160	...	...	1385	2260
0.190	...	...	...	2390
Rivet shear strength[c]	713	1090	1580	2855
	Yield Strength[d], lbs			
Sheet thickness, in.:				
0.040	146	...	...	...
0.050	228	226	...	...
0.063	395	369	343	...
0.071	496	495	444	...
0.080	526	640	615	...
0.090	561	769	806	660
0.100	595	811	1000	912
0.125	...	918	1195	1560
0.160	...	...	1375	2105
0.190	...	...	...	2310
Head height (ref.), in.	0.042	0.055	0.070	0.095

a Yield value is less than 2/3 of the indicated ultimate strength value.
b Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
c Rivet shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 55 ksi.
d Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.1(f). Static Joint Strength of Blind 100° Flush Head Aluminum Alloy (2117-T3) Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	MS20601AD and MS20603AD (F_{su} = 30 ksi)			
Sheet Material	Clad 2024-T3			
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)	1/4 (0.258)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.040	159[a]	...	...	...
0.050	236	258[a]	...	...
0.063	327	369	398[a]	...
0.071	360	439	485	...
0.080	388	511	577	...
0.090	...	561	684	795[a]
0.100	...	596	768	945
0.125	...	...	862	1270
Rivet shear strength[b]	388	596	862	1550
	Yield Strength[c], lbs			
Sheet thickness, in.:				
0.040	110	...	...	...
0.050	198	185	...	...
0.063	300	308	296	...
0.071	336	384	391	...
0.080	377	468	497	...
0.090	...	524	614	621
0.100	...	592	709	793
0.125	...	...	862	1150
Head height (ref.), in.	0.042	0.055	0.070	0.095

a Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.

b Rivet shear strength based on areas computed from nominal hole diameters in Table 8.1.2(a) and F_{su} = 30 ksi.

c Permanent set at yield load: the greater of 0.005 inch or 2.5% of nominal diameter.

Table 8.1.3.2.2(f). Static Joint Strength of Blind 100° Flush Head Aluminum Alloy (2219) Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	CR 2A62[a] (F_{su} = 36 ksi)		
Sheet Material	Clad 2024-T81		
Rivet Diameter, in. . . . . (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs		
Sheet thickness, in.			
0.050	203	...	...
0.063	289	319	...
0.071	342	385	...
0.080	393	461	503
0.090	416	542	603
0.100	439	610	701
0.125	478	682	894
0.160	...	741	1013
0.190	...	...	1063
Rivet shear strength[b]	478	741	1063
	Yield Strength[c], lbs		
Sheet thickness, in.:			
0.050	169	...	...
0.063	247	267	...
0.071	295	326	...
0.080	349	394	423
0.090	409	468	514
0.100	424	544	603
0.125	448	658	827
0.160	...	670	960
0.190	...	...	1002
Head height (ref.), in.	0.042	0.055	0.070

a Data supplied by Cherry Fasteners.
b Shear strength values are based on indicated nominal hole diameters and F_{su} = 36 ksi.
c Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.2.2(g). Static Joint Strength of Blind 100 degree Flush Head Locked Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	NAS1921B0()-0(), NAS1921B0()S0(), NAS1921B0()S0()U[a] (F_{su} = 36 ksi)		
Sheet Material	Clad 7075-T6		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet Thickness, in.:			
0.040	171[b]	---	---
0.050	232	267[b]	---
0.063	313	366	411[b]
0.071	360	427	484
0.080	416	498	566
0.090	477	571	658
0.100	494	647	748
0.125	---	755	978
0.160	---	---	1090
Rivet Shear Strength[c]	495	755	1090
	Yield Strength, lbs[d]		
Sheet Thickness, in.:			
0.040	110	---	---
0.050	161	171	---
0.063	247	254	270
0.071	303	315	330
0.080	354	395	399
0.090	373	484	506
0.100	393	549	611
0.125	---	610	803
0.160	---	---	906
Head Height [ref.], in.	0.042	0.055	0.070

a Data supplied by Huck Manufacturing Company.

b Values above the horizontal line in each column are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring activity.

c Rivet shear strength is documented in NAS1900.

d Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.2.2(n). Static Joint Strength of Blind 100° Flush Head Locked Spindle A-286 Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	NAS1721C and NAS1721C( )L[a] (F_{su} = 75 ksi)		
Sheet Material	Clad 7075-T6		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	454[c, d]	...	...
0.050	585[d]	707[c,d]	...
0.063	751[d]	919[d]	1075[c,d]
0.071	853[d]	1045[d]	1230[d]
0.080	881[d]	1190[d]	1405[d]
0.090	896	1345[d]	1595[d]
0.100	912	1365[d]	1785[d]
0.125	951	1415	1970
0.160	1000	1485	2055
0.190	...	1500	2125
0.250	...	...	2200
Rivet shear strength[e]	1000	1500	2200
	Yield Strength[f], lbs.		
Sheet thickness, in.:			
0.040	77	...	...
0.050	220	122	...
0.063	375	352	246
0.071	470	471	425
0.080	578	604	585
0.090	615	753	763
0.100	641	902	942
0.125	707	997	1330
0.160	799	1110	1470
0.190	...	1210	1585
0.250	...	...	1820
Head height (ref.), in.	0.042	0.055	0.070

a Data supplied by Avdel Corp.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, ±0.001 inch.
c The values in the table above the horizontal line in each column are for knife-edge conditions and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires the specific approval of the procuring agency.
d Yield value is less than 2/3 of indicated ultimate value.
e Rivet shear strength is documented in NAS1722.
f Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

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Table 8.1.3.2.2(q). Static Joint Strength of Blind Flush Head Locked Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheets

Rivet Type	HC3212 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet Thickness, in.:			
0.040	280[c,d]	---	---
0.050	318	436[c,d]	---
0.063	367	497	643[c,d]
0.071	397	535	688
0.080	431	577	739
0.090	469	624	795
0.100	507	671	851
0.125	602	789	992
0.160	664	954	1190
0.190	---	1030	1355
0.250	---	---	1480
Rivet Shear Strength[e]	664	1030	1480
	Yield Strength, lbs[f]		
Sheet Thickness, in.:			
0.040	151	---	---
0.050	244	236	---
0.063	366	387	382
0.071	397	480	494
0.080	431	577	619
0.090	454	624	758
0.100	476	671	851
0.125	532	740	979
0.160	610	837	1095
0.190	---	921	1195
0.250	---	---	1395
Head Height [ref.], in.	0.042	0.055	0.070

a Data supplied by Huck International Inc.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.
c The values in the table above the horizontal line in each column are for knife-edge conditions and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires specific approval of the procuring activity.
d Yield value is less than 2/3 of indicated ultimate strength value.
e Rivet shear strength is documented on HC3212 standards drawing.
f Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.2.2(v). Static Joint Strength of 100° Flush Shear Head Locked Spindle Aluminum Alloy Blind Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	HC6224[a] (F_{su} = 50 ksi) Nominal		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs		
Sheet thickness, in.:			
0.032	230	294[c]	
0.040	282	358	437[c]
0.050	347	439	534
0.063	431	544	660
0.071	456	608	737
0.080	493	681	824
0.090	535	716	921
0.100	576	768	979
0.125	664	897	1135
0.160	...	1030	1350
0.190	...	...	1480
Rivet shear strength[d]	664	1030	1480
	Yield Strength[e], lbs		
Sheet thickness, in.:			
0.032	185	209	
0.040	248	288	320
0.050	328	387	438
0.063	431	516	592
0.071	448	595	687
0.080	457	681	794
0.090	467	697	912
0.100	477	710	979
0.125	503	742	1030
0.160	...	786	1080
0.190	...	...	1125
Head height (ref.), in.	0.028	0.037	0.046

a Data supplied by Huck International, Inc.
b Yield value is less than 2/3 of the indicated ultimate.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring activity.
d Rivet shear strength is documented in MIL-R-7885D.
e Permanent set at yield load: 4% of nominal hole diameter (see 9.4.1.3.3).

Table 8.1.3.2.2(w). Static Joint Strength of Blind Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheets

Rivet Type	AF3212 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet Thickness, in.:			
0.040	143[c]	---	---
0.050	247	224[c]	---
0.063	383	393	370[c]
0.071	414	497	494
0.080	435	614	634
0.090	457	647	790
0.100	480	676	902
0.125	537	746	987
0.160	616	846	1105
0.190	---	931	1205
0.250	---	---	1410

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

Rivet Shear Strength[d]	664	1030	1480
	Yield Strength, lbs[e]		
Sheet Thickness, in.:			
0.040	143	---	---
0.050	235	224	---
0.063	310	371	370
0.071	330	431	491
0.080	353	486	572
0.090	379	518	662
0.100	404	549	713
0.125	468	629	808
0.160	557	740	914
0.190	---	835	1055
0.250	---	---	1280
Head Height [ref.], in.	0.042	0.055	0.070

a Data supplied by Allfast Fastening Systems Inc.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.
c The values in the table above the horizontal line in each column are for knife-edge conditions, and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires specific approval of the procuring activity.
d Rivet shear strength is documented on AF3212 standards drawing.
e Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.2.2(x). Static Joint Strength of Blind Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	CR3212 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet Thickness, in.:			
0.040	297[c,d]	---	---
0.050	342[d]	462[d]	---
0.063	401[d]	535[d]	683[d]
0.071	437[d]	580[d]	737[d]
0.080	477	630[d]	798[d]
0.090	513	687[d]	865[d]
0.100	536	743	932
0.125	594	834	1100

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

Rivet Shear Strength[e]	664	1030	1480
	Yield Strength, lbs[f]		
Sheet Thickness, in.:			
0.040	131	---	---
0.050	181	204	---
0.063	247	286	317
0.071	287	336	377
0.080	333	393	444
0.090	361	456	520
0.100	371	518	595
0.125	394	576	783
Head Height [ref.], in.	0.042	0.055	0.070

a Data supplied by Textron Aerospace Fasteners.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.
c The values in the table above the horizontal line in each column are for knife-edge conditions, and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires specific approval of the procuring activity.
d Yield value is less than 2/3 of indicated ultimate strength value.
e Rivet shear strength is documented on CR3212 standards drawing.
f Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.2.2(y). Static Joint Strength of Blind Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	AF3242 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.		
Sheet Thickness, in.:			
0.032	193[c]	---	---
0.040	250	299[c]	---
0.050	321	387	---
0.063	414	501	573[c]
0.071	470	571	654
0.080	524	651	746
0.090	550	738	849
0.100	577	804	951
0.125	643	886	1120
0.160	736	1000	1250
0.190	814	---	1365
Rivet Shear Strength[d]	814	1245	1685
	Yield Strength, lbs[e]		
Sheet Thickness, in.:			
0.032	192	---	---
0.040	250	298	---
0.050	321	387	---
0.063	414	501	573
0.071	470	571	654
0.080	524	651	746
0.090	550	738	849
0.100	577	804	951
0.125	643	886	1120
0.160	736	1000	1250
0.190	814	---	1365
Head Height (ref.), in.	0.035	0.047	0.063

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

a Data supplied by Allfast Fastening Systems Inc.
b Loads developed from tests with hole diameters of 0.144, 0.178, and 0.207, +/-0.001 inch.
c The values in the table above the horizontal line in each column are for knife-edge conditions, and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires the specific approval of the procuring activity.
d Rivet shear strength is documented on AF3242 standards drawing.
e Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.2.2(z). Static Joint Strength of Blind Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	CR3242 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.		
Sheet Thickness, in.:			
0.032	245[c,d]	---	---
0.040	302	378[c,d]	---
0.050	374	467	---
0.063	467	582	681[c]
0.071	568	653	764
0.080	584	732	856
0.090	602	872	959
0.100	620	894	1165
0.125	664	950	1230
Rivet Shear Strength[e]	814	1245	1685
	Yield Strength, lbs[f]		
Sheet Thickness, in.:			
0.032	158	---	---
0.040	206	245	---
0.050	265	318	---
0.063	330	413	472
0.071	361	471	540
0.080	395	514	616
0.090	434	562	678
0.100	473	609	734
0.125	569	729	873
Head Height (ref.), in.	0.035	0.047	0.063

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

a Data supplied by Textron Aerospace Fasteners.
b Loads developed from tests with hole diameters of 0.144, 0.178, and 0.207, +/-0.001 inch.
c The values in the table above the horizontal line in each column are for knife-edge conditions, and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires the specific approval of the procuring activity.
d Yield value is less than 2/3 of indicated ultimate strength value.
e Rivet shear strength is documented on CR3242 standards drawing.
f Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.2.2(aa). Static Joint Strength of Blind Flush Head Locked Spindle Aluminum Alloy Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	HC3242 (F_{su} = 51 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.[b]	1/8 (0.144)	5/32 (0.178)	3/16 (0.207)
	Ultimate Strength, lbs.		
Sheet Thickness, in.: 0.032	267[c,d]	---	---
0.040	310	411[c,d]	---
0.050	363	477	---
0.063	433	563	682[c]
0.071	475	616	744
0.080	522	675	813
0.090	560	741	889
0.100	597	803	966
0.125	690	918	1130
0.160	814	1075	1320
0.190	---	1215	1480
0.250	---	---	1685
Rivet Shear Strength[e]	814	1245	1685
	Yield Strength, lbs[f]		
Sheet Thickness, in.: 0.032	138	---	---
0.040	218	217	---
0.050	317	340	---
0.063	433	500	529
0.071	475	598	643
0.080	510	675	772
0.090	527	741	889
0.100	543	781	966
0.125	585	833	1075
0.160	644	906	1160
0.190	---	968	1235
0.250	---	---	1375
Head Height (ref.), in.	0.035	0.047	0.063

THIS FASTENER HAS ONLY BEEN TESTED IN THE SHEET GAGES SHOWN IN THIS TABLE. DESIGN DATA FOR SHEET GAGES OR DIAMETERS OTHER THAN THOSE SHOWN HERE CANNOT BE EXTRAPOLATED.

a Data supplied by Huck International Inc.
b Loads developed from tests with hole diameters of 0.144, 0.178, and 0.207, +/-0.001 inch.
c The values in the table above the horizontal line in each column are for knife-edge conditions, and the use of fasteners in this condition is undesirable. The use of knife-edge conditions in the design of military aircraft requires the specific approval of the procuring activity.
d Yield value is less than 2/3 of indicated ultimate strength value.
e Rivet shear strength is documented on HC3242 standards drawing.
f Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.2.2(bb). Static Joint Strength of Blind Flush Head Locked Spindle Aluminum Alloy Rivets in Aluminum Alloy Sheet

Rivet Type	AF3222 (F_{su} = 50 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	202[c]	...	...
0.050	287	316[c]	...
0.063	388	452	492[c]
0.071	412	536	593
0.080	439	608	706
0.090	469	645	832
0.100	498	683	891
0.125	573	775	1000
0.160	664	905	1155
0.190	...	1015	1290
0.250	...	1030	1480
Rivet shear strength[d]	664	1030	1480
	Yield Strength[e], lbs.		
Sheet thickness, in.:			
0.040	160	...	...
0.050	216	249	...
0.063	290	341	383
0.071	335	397	451
0.080	379	460	527
0.090	421	531	611
0.100	462	591	696
0.125	566	720	880
0.160	664	901	1095
0.190	...	1015	1280
0.250	...	1030	1480
Head height (ref.), in.	0.042	0.055	0.070

a Data supplied by Allfast Fastening Systems Inc.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.001 inch.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in the design of military aircraft requires specific approval of the procuring agency.
d Rivet shear strength as documented in Allfast Fastening Systems Inc. P-127.
e Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.2.2(cc). Static Joint Strength of Flush Head 5056 Aluminum Alloy Rivets in Clad Aluminum Alloy Sheet

Rivet Type	CR3222 (F_{su} = 50 ksi approx.)[a]		
Sheet Material	Clad 2024-T3		
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.130)	5/32 (0.162)	3/16 (0.194)
	Ultimate Strength, lbs.		
Sheet thickness, in.:			
0.040	286[c,d]	...	...
0.050	328[d]	445[c,d]	...
0.063	382[d]	513[d]	658[c,d]
0.071	416	555[d]	708[d]
0.080	454	602[d]	764[d]
0.090	496	654	827[d]
0.100	528	706	889
0.125	589	821	1045
0.160	664	928	1215
0.190	...	1020	1325
0.250	...	1030	1480
Rivet shear strength[e]	664	1030	1480
	Yield Strength[f], lbs.		
Sheet thickness, in.:			
0.040	158	...	...
0.050	199	247	...
0.063	252	313	373
0.071	285	354	422
0.080	322	399	476
0.090	362	450	537
0.100	384	501	598
0.125	425	597	750
0.160	483	669	881
0.190	...	731	955
0.250	...	854	1100
Head height (ref.), in.	0.041	0.054	0.069

a Data supplied by Textron Aerospace Fasteners.
b Loads developed from tests with hole diameters of 0.130, 0.162, and 0.194, +/- 0.0005 inch.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in the design of military aircraft requires the specific approval of the procuring agency.
d Yield values is less than 2/3 of indicated ultimate strength value.
e Rivet shear strength as documented in Textron Aerospace Fasteners PS-CMR-3000.
f Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.3.2.3(a). Static Joint Strength of Blind 100° Flush Head A-286 Bolts in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	MS21140[a] (F_{su} = 95 ksi)				
Sheet and Plate Material	Clad 7075-T6 and T651				
Fastener Diameter, in. . . . . (Nominal Shank Diameter, in.)	5/32 (0.163)	3/16 (0.198)	1/4 (0.259)	5/16 (0.311)	3/8 (0.373)
	Ultimate Strength, lbs				
Sheet or plate thickness, in.:					
0.071	1165[b]	...	...	...	...
0.080	1330[b]	[c] 1600[b]	...	...	...
0.090	1515[b]	1805[b]	[c] ...	...	...
0.100	1700[b]	2020[b]	2615[b]	...	...
0.125	1980[b]	2595[b]	3295[b]	[c] 3935[b]	...
0.160	...	2925[b]	4335[b]	5080[b]	[c] 6010[b]
0.190	...	...	5005[b]	6150[b]	7205[b] [c]
0.200	...	...	...	6520[b]	6580[b]
0.250	...	...	...	7215[b]	9810[b]
0.312	...	...	...	...	10380[b]
Fastener shear strength[d]	1980	2925	5005	7215	10380
	Yield Strength[e], lbs				
Sheet or plate thickness, in.:					
0.071	478	...	...	...	...
0.080	584	627	...	...	...
0.090	702	730	...	...	...
0.100	819	901	1025	...	...
0.125	1115	1260	1435	1540	...
0.160	...	1760	2090	2285	2430
0.190	...	...	2655	2965	3235
0.200	...	...	...	3190	3510
0.250	...	...	...	4320	4860
0.312	...	...	...	...	6460
Head height (ref.), in.	0.074	0.082	0.108	0.140	0.168

a Data supplied by Huck Manufacturing Company.
b Yield value is less than 2/3 of the indicated ultimate strength value.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
d Fastener shear strength is documented in MIL-F-8975.
e Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3) (revised May 1, 1986, from the greater of 0.012 inch or 4% of nominal diameter).

Table 8.1.3.2.3(b$_1$). Static Joint Strength of Blind 100° Flush Head Alloy Steel Fasteners in Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	MS90353, MS90353S, and MS90353U[a] (F_{su} = 112 ksi)				
Sheet and Plate Material	Clad 2024-T3 and T351				
Fastener Diameter, in. (Nominal Shank Diameter, in.)	5/32 (0.163)	3/16 (0.198)	1/4 (0.259)	5/16 (0.311)	3/8 (0.373)
	Ultimate Strength, lbs				
Sheet or plate thickness, in.:					
0.071	1120[b,c]	...	...	...	...
0.080	1305[b]	1480[b,c]	...	...	...
0.090	1510[b]	1735[b]	...	...	...
0.100	1740[b]	2000[b]	2380[b,c]	...	...
0.125	2080[b]	2670[b]	3210[b]	3625[b,c]	...
0.160	2340[b]	3195[b]	4440[b]	5060[b]	5700[b,c]
0.190	...	3450[b]	5090[b]	6310[b]	7180[b]
0.250	...	...	5900[b]	7860[b]	9890[b]
0.312	...	...	...	8500[b]	11600[b]
0.375	...	...	...	...	12200[b]
Fastener shear strength[d]	2340	3450	5900	8500	12200
	Yield Strength[e], lbs				
Sheet or plate thickness, in.:					
0.071	403	...	...	...	...
0.080	513	501	...	...	...
0.090	636	652	...	...	...
0.100	759	799	1045	...	...
0.125	989	1170	1525	1620	...
0.160	1170	1510	2200	2430	2610
0.190	...	1700	2700	3120	3440
0.250	...	...	3330	4170	5095
0.312	...	...	...	4955	6175
0.375	...	...	...	...	7135
Head height (ref.), in.	0.072	0.080	0.105	0.137	0.165

a Data supplied by Huck Manufacturing Company.
b Yield strength value is less than 2/3 of indicated ultimate strength value.
c Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
d Fastener shear strength is documented in MIL-F-81177.
e Permanent set at yield load: 4% of nominal diameter (Ref. 9.4.1.3.3).

Table 8.1.5.2(d). Static Joint Strength of 100° Flush Head Tapered STA Ti-6Al-4V Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	TLV 10[a] (F_{su} = 95 ksi)			
Sheet Material	Clad 7075-T6			
Fastener Diameter, in. (Nominal Shank Diameter, in.)	1/8 (0.1437)	5/32 (0.1688)	3/16 (0.1965)	1/4 (0.2583)
	Ultimate Strength, lbs			
Sheet thickness, in.:				
0.032	488	...	...	...
0.040	610	[b] 713	826	...
0.050	768	896	1050	[b] ...
0.063	967	1145	1312	1730
0.071	1120	1290	1491	1960 [b]
0.080	1260	1470	1690	2223
0.090	1377	1670	1910	2505
0.100	1441	1845	2130	2800
0.125	1530	2010	2580	3540
0.160	1540	2125	2800	4410
0.190	...	...	2880	4750
0.250	...	...	...	4980
Fastener shear strength[c]	1540	2125	2880	4980
	Yield Strength[d], lbs			
Sheet thickness, in.:				
0.032	488	...	...	...
0.040	610	713	826	...
0.050	753	890	1050	...
0.063	925	1118	1301	1730
0.071	1035	1240	1467	1960
0.080	1138	1377	1637	2192
0.090	1238	1522	1806	2455
0.100	1321	1639	1976	2711
0.125	1480	1880	2331	3304
0.160	1540	2111	2683	3986
0.190	...	...	2880	4437
0.250	...	...	...	4980
Head height (max.), in.	0.033	0.041	0.048	0.063

a Data supplied by Lockheed Georgia Company.
b Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
c Fastener shear strength based on areas computed from indicated nominal shank diameter and F_{su} = 95 ksi.
d Permanent set at yield load: the greater of 0.012 inch or 4% of fractional diameter.

Table 8.1.5.2(e). Static Joint Strength of 70° Flush Head Tapered Ti-6Al-4V Fasteners in Non-Matching Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	HPB-V[a] (F_{su} = 95 ksi)			
Sheet and Plate Material	Clad 7075-T6 and T651			
Fastener Diameter (Nominal Shank Diameter, in.)[b]	3/16 (0.1976)	1/4 (0.2587)	5/16 (0.3211)	3/8 (0.3850)
Sheet Countersink Angle	82°	82°	82°	75°
	Ultimate Strength, lbs			
Sheet or plate thickness, in.:				
0.063	1355	...	...	...
0.071	1554	2041	...	...
0.080	1710	2296	...	...
0.090	1847	2583	3207	...
0.100	1984	2864	3567	4269
0.125	2319	3293	4454	5336
0.160	2792	3908	5176	6611
0.190	2913	4444	5836	7396
0.250	...	4993	7155	8968
0.312	...	...	7692	10613
0.375	...	...	...	11058
0.500	...	...	...	11058
Fastener shear strength[c]	2913	4993	7692	11058
	Yield Strength[d], lbs			
Sheet or plate thickness, in.:				
0.063	1269	...	...	...
0.071	1429	1874	...	...
0.080	1613	2108	...	...
0.090	1812	2376	2949	...
0.100	1984	2637	3279	3928
0.125	2319	3299	4093	4906
0.160	2718	3908	5176	6285
0.190	2913	4397	5836	7396
0.250	...	4993	6980	8968
0.312	...	...	7692	10257
0.375	...	...	...	11058
0.500	...	...	...	11058
Head height (max.), in.	0.057	0.067	0.076	0.086

a Data supplied by PB Fasteners.
b Fasteners installed in interference holes (0.0015-0.0048) (Ref. Section 8.1.5).
c Fastener shear strength based on areas computed from the indicated nominal shank diameter and F_{su} = 95 ksi.
d Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(l). Static Joint Strength of 70° Flush Head Straight Shank Ti-6Al-4V Fasteners in Non-Matching Machine-Countersunk Aluminum Alloy Sheet and Plate

Fastener Type	HPT-V[a] (F_{su} = 95 ksi)			
Sheet and Plate Material	Clad 7075-T6 and T651			
Fastener Diameter (Nominal Shank Diameter, in.)[b]	3/16 (0.193)	1/4 (0.255)	5/16 (0.3175)	3/8 (0.380)
Sheet Countersink Angle	82°	82°	82°	75°
	Ultimate Strength, lbs			
Sheet or plate thickness, in.:				
0.063	1348	...	...	...
0.071	1546	1970	...	...
0.080	1704	2275	...	...
0.090	1814	2580	3125	...
0.100	1948	2873	3528	4100
0.125	2265	3282	4465	5270
0.160	2700	3868	5171	6642
0.190	2779	4361	5826	7393
0.250	...	4851	7056	8880
0.312	...	...	7521	10396
0.375	...	...	...	10774
Fastener shear strength[c]	2779	4851	7521	10774
	Yield Strength[d], lbs			
Sheet or plate thickness, in.:				
0.063	1180	...	...	...
0.071	1378	1651	...	...
0.080	1590	1944	...	...
0.090	1702	2321	2631	...
0.100	1818	2620	3024	3350
0.125	2112	3055	4133	4664
0.160	2496	3601	4848	6209
0.190	2734	4062	5413	6902
0.250	...	4745	6552	8288
0.312	...	...	7378	9631
0.375	...	...	...	10584
Head height (max.), in.	0.060	0.070	0.080	0.090

a Data supplied by PB Fasteners.

b Fasteners installed in interference holes (0.0045-0.0055) (Ref. 8.1.5).

c Fastener shear strength based on areas computed from the indicated nominal shank diameter and F_{su} = 95 ksi.

d Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

Table 8.1.5.2(m). Static Joint Strength of 100° Flush Shear Head STA Ti-6Al-4V Fasteners in Machine-Countersunk Aluminum Alloy Sheet

Fastener Type	NAS 4452V Pin (F_{su} = 95 ksi), NAS 4445D Nut[a]				
Sheet Material	Clad 7075-T6				
Fastener Diameter, in. (Nominal Shank Diameter, in.)	5/32 (0.164)	3/16 (0.190)	1/4 (0.250)	5/16 (0.312)	3/8 (0.375)
	Ultimate Strength, lbs				
Sheet or plate thickness, in.:					
0.040	766	...	...	...	...
0.050	1092	[b] 1173	...	...	...
0.063	1450	1639	1886	...	...
0.071	1633	1889	2290	[b] ...	...
0.080	1805	2136	2710	3028	...
0.090	1955	2368	3135	3651	...
0.100	2007	2557	3515	4230	4669
0.125	...	2694	4273	5485	6428
0.160	...	...	4660	6776	8426
0.190	...	...	...	7290	9708
0.250	...	...	...	...	10490
Fastener shear strength[c]	2007	2694	4660	7290	10490
	Yield Strength[d], lbs				
Sheet thickness, in.:					
0.040	712	...	...	...	...
0.050	891	1034	...	...	...
0.063	1103	1295	1712	...	...
0.071	1223	1445	1932	...	...
0.080	1349	1604	2169	2715	...
0.090	1475	1768	2420	3056	...
0.100	1489	1920	2658	3383	4082
0.125	...	2241	3196	4145	5072
0.160	...	...	3812	5076	6321
0.190	...	...	...	5746	7265
0.250	...	...	...	...	8802
Head height (max.), in.	0.040	0.049	0.063	0.077	0.091

a Data supplied by Huck Manufacturing Company.
b Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency.
c Fastener shear strength is documented in NAS 4444.
d Permanent set at yield load: the greater of 0.012 inch or 4% of nominal diameter.

CHAPTER 9

GUIDELINES FOR THE PRESENTATION OF DATA

This chapter contains Guidelines for judging adequacy of data, procedures for analyzing data in determining property values for inclusion in previous chapters, and formats for submitting results of analyses to the MIL-HDBK-5 Coordination Group for approval.

The following index can be used to locate sections of the Guidelines applicable to various properties:

9.0 SUMMARY

The objective of this summary is to provide a global overview of Chapter 9 without defining specific statistical details. This overview will be most helpful to those unfamiliar with the statistical procedures used in MIL-HDBK-5 and to those who would like to learn more about the philosophy behind the MIL-HDBK-5 guidelines.

Chapter 9 is the "rule book" for MIL-HDBK-5. Since 1966, these guidelines have described statistical procedures used to calculate mechanical properties for alloys included in the Handbook. Recommended changes in the guidelines are reviewed first by the Guidelines and Emerging Materials Task Group (GEMTG) and later approved by the entire coordination committee. Recommended changes in statistical procedures within the guidelines are evaluated first by the Statistics Working Group (SWG), which supports the GEMTG. Similarly, recommended changes in fastener analysis procedures are examined by the Fastener Task Group (FTG) before approval by the coordination committee.

Chapter 9 is divided into 6 subchapters which cover the analysis methods used to define room and elevated temperature properties. The room temperature mechanical properties are tensile, compression, bearing, shear, fatigue, fracture toughness, elongation and elastic modulus. The elevated temperature properties are the same, except that creep and stress rupture properties are added to the list. Analysis procedures for fatigue, fatigue crack growth and mechanically fastened joints are also covered since these data are commonly used in aircraft design. The presentation of these data varies depending upon the data type. For instance, the room temperature mechanical properties (tensile, compression, bearing, shear, elongation and elastic modulus) are provided in a tabular format, while the fatigue, elevated temperature properties, and typical stress-strain curves are presented in graphical format.

Before an alloy can be considered for inclusion in MIL-HDBK-5, it must be covered by a commercial or government specification. There are two main reasons for this: (1) the alloy, and its method of manufacture, must be "reduced to standard practice" to increase confidence that the material, if obtained from different suppliers, will still demonstrate similar mechanical properties, and (2) specification minimum properties are included in MIL-HDBK-5 tables as design properties in situations where there are insufficient data to determine statistically based material design values.

The majority, by far, of the data in MIL-HDBK-5 are room temperature design properties: including tensile (F_{tu}, F_{ty}), shear (F_{su}), compression (F_{cy}), bearing strengths (F_{bru} and F_{bry}), elongation and elastic modulus. Room temperature design properties are the primary focus in the Handbook because most aircraft, commercial and military, typically operate at near-ambient temperatures and because most material specifications include only room temperature property requirements.

Design minimum mechanical properties tabulated in MIL-HDBK-5 are calculated either by "direct" or "indirect" statistical procedures. The minimum sample size required for the direct computation of T_{99} and T_{90} values (from which A and B-basis design properties are established) is 100. These 100 observations must include data from at least 10 heats and lots (as defined in the next paragraph). A T_{99} value is a statistically computed, one-sided lower tolerance limit, representing a 95 percent confidence lower limit on the first percentile of the distribution. Similarly, a T_{90} value is a statistically computed, one-sided lower tolerance limit, representing a 95 percent lower confidence limit on the tenth percentile of the distribution. If the sample cannot be described by a Pearson[1] or Weibull distribution, the T_{99} and T_{90} values must be computed by nonparametric (distribution free) means, which can only be done if there are at least 299 observations.

[1]A Pearson distribution analysis with zero skewness is comparable to the normal analysis method used in earlier versions of MIL-HDBK-5.

In most cases, only minimum tensile ultimate and yield strength values are determined by the direct method. T_{90} values are not computed if there are insufficient data to compute T_{99} values, even though a much smaller sample size is required to compute nonparametric T_{90} values. This is because the general consensus within the MIL-HDBK-5 committee has been that a large number of observations (in the realm of 100) are needed from a large number of heats and lots (e.g. 10) for a particular material to properly characterize the variability in strength of that product.

A lot represents all of the material of a specific chemical composition, heat treat condition or temper, and product form that has passed through all processing operations at the same time. Multiple lots can be obtained from a single heat. A heat of material, in the case of batch melting, is all of the material that is cast at the same time from the same furnace and is identified with the same heat number. In the case of continuous melting, a single heat of material is generally poured without interruption. The exception is for ingot metallurgy wrought aluminum products, where a single heat is commonly cast in sequential aluminum ingots, which are melted from a single furnace change and poured in one or more drops without changes in the processing parameters (see Table 9.1.6.2).

Minimum compression, bearing, and shear strengths are typically determined through the indirect method. This is done to reduce cost, because as few as 10 data points (from 3 heats and 10 lots) can be used, in combination with "paired" direct properties to compute a design minimum value. In this indirect method, the compression, bearing, and shear strengths are paired with tensile values determined in the same region of the product to produce a ratio. Statistical analyses of these ratios are conducted to obtain lower bound estimates of the relationship between the primary property and the ratioed property. These ratios are then multiplied with the appropriate F_{tu} or F_{ty} in the Handbook to obtain the F_{su}, F_{cy}, F_{bru}, F_{bry} values for shear, compression, and bearing (ultimate and yield), respectively.

Many mechanical property tables in the Handbook include data for specific grain directions and thickness ranges. This is done to better represent anisotropic materials, such as wrought products, that often display variations in mechanical properties as a function of grain direction and/or product thickness. Therefore, it is common practice to test for variability in mechanical properties as a function of product thickness. This is done through the use of regression analysis for both direct and indirect properties. If a regression is found to be significant, properties may be computed separately (without regression) for reduced thickness ranges.

To compliment the mechanical property tables, the Handbook also contains typical stress-strain curves. These curves are included to illustrate each material's yield behavior and to graphically display differences in yield behavior for different grain directions, tempers, etc. These curves are identified as typical because they are based upon only a few test points. Typical curves are shown for both tension and compression and are extended to just beyond the 0.2 percent yield stress. Each typical curve also contains a shape factor called the Ramberg-Osgood number (n). These numbers can be used in conjunction with a material's elastic modulus to empirically develop a stress-strain curve. Typical tensile full-range stress-strain curves are also provided that illustrate deformation behavior from the proportional limit to fracture. In addition, compression tangent-modulus curves are provided to describe compression instability.

Effect of temperature and thermal exposure curves are included throughout the Handbook. For tensile properties, the curves are presented as a percentage of the room temperature design value. For these curves, there is a minimum data requirement and statistical procedures have been established to construct the curves. The creep rupture plots are shown as typical isothermal curves of stress versus time. The physical properties are shown as a function of temperature for each property, i.e., specific heat, thermal conductivity, etc. Physical properties are reported as average actual values, not a percentage of a room temperature value.

In addition to the mechanical properties, statistically based S/N fatigue curves are provided in the Handbook, since many airframe structures experience dynamic loading conditions. The statistical procedures are fairly rigorous. For example, the procedure describes how to treat outliers and run-outs (discontinued tests), and which models to use to best-fit a specific set of data. Each fatigue figure includes relevant information such as K_t, R value, material properties, sample size and equivalent stress equation. Each figure should be closely examined by the user to properly identify the fatigue curves required for a particular design.

Design properties for mechanical fasteners and mechanically fastened elements are also included in MIL-HDBK-5. A unique analysis procedure has been developed for mechanical fasteners because fasteners generally do not develop the full bearing strength of materials in which they are installed. Realistic joint allowables are determined from test data using the statistical analysis procedures described in Chapter 9. There are four different types of fasteners for which design allowables must be determined, as described in Section 4.

The last section in the Handbook (Section 6) provides a detailed description of statistical procedures used in Chapter 9 for the analysis of data. Most of these procedures are backed up with examples and appropriate statistical tables.

9.0.1 TESTING STANDARDS — Testing standards used in MIL-HDBK-5 are summarized in Table 9.0.1. In most cases, testing standards maintained by the American Society for Testing and Materials, ASTM, are referenced. The primary exception is fastener testing, where NASM-1312 is used as the reference standard. The mostly recently approved version of each standard is used as the baseline for all test data reviewed for inclusion in MIL-HDBK-5.

9.0.2 DATA REQUIREMENTS — Data requirements for determination of mechanical and physical properties within MIL-HDBK-5 are summarized in Table 9.0.2. The customary statistical basis of each material property is listed, along with the relative importance of each data type within the Handbook. Potential extenuating circumstances, such as special material usage requirements, are also considered. Where applicable for each data type, the minimum sample size and the minimum number of heats and lots are identified. Applicable MIL-HDBK-5 introductory or guideline sections are also referenced.

Table 9.0.1. Summary of Recommended Testing Standards within MIL-HDBK-5

Property to be Determined or Procedure to be Followed	Designation	Title of Testing Standard	Relevant Section(s) within Guidelines
Bearing	ASTM E 238	Method for Pin-Type Bearing Test of Metallic Materials	9.1.6.4, 1.4.7.1, 3.1.2
Classification of Extensometers	ASTM E 83	Method of Verification and Classification of Extensometers	9.1.6.6, 9.3.2.2
Coefficient of Thermal Expansion	ASTM E 228	Test Method for Linear Thermal Expansion of Solid Materials with a Vitreous Silica Dilatometer	9.2.14
Compression	ASTM E 9	Compression Testing of Metallic Materials	1.7.1
Creep and Rupture	ASTM E 139	Rec. Practice for Conducting Creep, Creep-Rupture, & Stress-Rupture Tests of Metallic Materials	9.3.6.3
Density	ASTM C 693	Test Method for Density of Glass by Buoyancy	9.2.14
Elastic Modulus – Compression	ASTM E 111	Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus	9.1.6.6, 9.2.13
Elastic Modulus – Shear	ASTM E 143	Test Method for Shear Modulus at Room Temperature	9.2.13
Elastic Modulus – Tension	ASTM E 111	Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus	9.1.6.6, 9.2.13
Elongation	ASTM E 8	Test Method for Tension Testing of Metallic Materials	1.4.3.5
Exfoliation Corrosion	ASTM G 34	Test Method for Exfoliation Corrosion Susceptibility in 2XXX and 7XXX Series Aluminum Alloys (EXCO Test)	3.1.2.3.1
Fastener Mechanical Properties	NASM-1312	Fastener Test Methods	9.4.1.3.1
Fatigue - Load Control	ASTM E 466	Recommended Practice for Constant Amplitude Axial Fatigue Tests of Metallic Materials	9.3.4.1
Fatigue - Strain Control	ASTM E 606	Recommended Practice for Constant Amplitude Low Cycle Fatigue Testing	9.3.4.1
Fatigue Crack Growth	ASTM E 647	Test Method for Measurements of Fatigue Crack Growth Rates	9.3.5.2

Table 9.0.1. Summary of Recommended Testing Standards within MIL-HDBK-5, Continued

Property to be Determined or Procedure to be Followed	Designation	Title of Testing Standard	Relevant Section(s) within Guidelines
Fracture Toughness - Plane Strain	ASTM E 399	Test Method for Plane-Strain Fracture Toughness of Metallic Materials	9.5.1
Fracture Toughness - Plane Stress	ASTM E 561	Recommended Practice for R Curve Determination	9.5.1
Poisson's Ratio	ASTM E 132	Test Method for Poisson's Ratio at Room Temperature	9.2.13
Reduction in Area	ASTM E 8	Test Method for Tension Testing of Metallic Materials	1.4.3.5
Shear – Pin	ASTM B 769	Test Method for Shear Testing of Aluminum Alloys	9.1.6.4, 3.1.2
Shear – Slotted	ASTM B 831	Standard Test Method for Shear Testing of Thin Aluminum Alloy Products	9.1.6
Specific Heat	ASTM D 2766	Test Method for Specific Heat of Liquids and Solids	9.2.14
Stress Corrosion Cracking	ASTM G 47	Test Method for Determining Susceptibility to Stress-Corrosion Cracking of High Strength Aluminum Alloy Products	3.1.2.3.1
Tension	ASTM E 8	Test Method for Tension Testing of Metallic Materials	1.4.4.1
	ASTM B 557	Test Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products	1.4.4.1
Tension - Elevated Temperatures	ASTM E 21	Recommended Practice for Elevated Temperature Tension Tests of Metallic Materials	1.4.4.1
Thermal Conductivity	ASTM C 714	Test Method for Thermal Diffusivity of Carbon and Graphite by a Thermal Pulse Method	9.2.14

Table 9.0.2. Summary of Data Requirements within MIL-HDBK-5

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MIL-HDBK-5	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements			Applicable Handbook Sections
				Sample Size	No. of Heats	No. of Lots	
Bearing Yield and Ultimate Strength	Derived form Paired Tensile Tests	Mandatory	Except for elevated temperature applications	20	3	10	9.1.6.4, 1.4.7.1, 3.1.2
Coefficient of Thermal Expansion	Typical	Strongly recommended	Especially for anticipated range of usage	Triplicate measurements			9.2.14
Compression Yield Strength	Derived from Paired Tensile Tests	Mandatory		20	3	10	1.7.1
Creep and Rupture	Raw Data w/ Best-Fit Curves	Recommended	Especially for elevated temperature applications	6 tests per creep strain level and temp, at least 4 temps over usage range			9.3.6.3
Density	Typical	Mandatory		Duplicate measurements			9.2.14
Elastic Modulus (Tension and Compression)	Typical	Mandatory	Clad materials must have primary and secondary modulus properties defined	9	3	Multi-ple	9.1.6.6, 9.2.13
Elastic Modulus (T and C) - Elevated Temperatures	Typical	Mandatory	For anticipated usage range	9	3	Multi-ple	9.2.13
Elongation	S-basis	Mandatory	Two-inch gage length preferred	30	3	10	1.4.3.5
Fastener Yield and Ultimate Load	B-basis	Mandatory		100	3	10	9.4.1.3.1
Fastener Shear Strength	B-basis	Mandatory	At least 15 tests per fastener diameter	100	3	10	9.4
Fatigue-Load Control	Raw Data w/ Best-Fit Curves	Recommended	Especially for high-cycle fatigue critical applications	6 tests per R ratio, 3 R ratios, no minimum heat or lot requirements			9.3.4.5
Fatigue-Strain Control	Raw Data w/ Best-Fit Curves	Recommended	Especially for low-cycle fatigue critical applications	10 tests for R_ε = -1.0, 6 tests other strain ratios			9.3.4.5

Table 9.0.2. Summary of Data Requirements within MIL-HDBK-5, Continued

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MIL-HDBK-5	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements			Applicable Handbook Sections
				Sample Size	No. of Heats	No. of Lots	
Fatigue Crack Growth	Raw Data w/ Best-Fit Curves	Recommended	Especially for damage tolerance critical applications	Duplicate da/dN results for relevant stress ratios and stress intensity range			9.3.5.3
Fracture Toughness - Plane Strain	Basic Statistical Information	Recommended	Mandatory for materials with spec. min. requirements for plane strain fracture toughness	30	3	10	9.5.1
Fracture Toughness - Plane Stress	Raw Data w/ Best-Fit Curves	Recommended	Mandatory for materials with spec minimum requirements for plane stress fracture toughness	a	2	5	9.5.1
Poisson's Ratio	Typical	Strongly recommended		Duplicate measurements			9.2.13
Reduction In Area	Typical	Recommended		When tested, use same criteria as for elongation			9.2.15
Shear Ultimate Strength	Derived from Paired Tensile Tests	Mandatory	Except for elevated temperature applications	20	3	10	1.4.6.4, 9.1.6.4
Specific Heat	Typical	Strongly recommended	Important to document over anticipated usage range	Duplicate measurements			9.2.14
Stress Corrosion Cracking	Letter Rating	Recommended	Especially for susceptible aluminum alloys	Conform to replication requirements in G47			3.1.2.3
Stress/Strain Curves (To Yield)	Typical	Mandatory	Desirable to have accurate plastic strain offsets from 10^{-6} to 3×10^{-2}	6	3	6	9.3.2
Stress/Strain Curves (Full Range)	Typical	Mandatory		6	3	6	9.3.2

Table 9.0.2. Summary of Data Requirements within MIL-HDBK-5, Continued

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MIL-HDBK-5	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements			Applicable Handbook Sections
				Sample Size	No. of Heats	No. of Lots	
Tension Yield and Ultimate Strength	S-basis	Mandatory		30	3	Multi-ple	1.4.4.1
Tension Yield and Ultimate Strength	A- and B-basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is possible	100	10	10	1.4.4.1
Tension Yield and Ultimate Strength	A- and B-basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is not possible	300	10	10	1.4.4.1
Tension Yield and Ultimate Strength - Elevated Temps	Typical	Recommended	Mandatory for elevated temperature applications	b	2	5	1.4.4.1
Thermal Conductivity	Typical	Strongly recommended	Important to document over anticipated usage range	Duplicate measurements			9.2.14

a Minimum sample size not specified, testing should be conducted at 6 or more panel widths to confidently represent trends over the panel widths of interest. Refer to ASTM E561 for testing details.

b Minimum sample size not specified, testing should be conducted at 6 or more temperatures to confidently represent trends over the temperature range of interest. Testing in regions where properties are expected to change rapidly with changes in temperature must be done at temperature intervals sufficiently small to clearly identify mean trends.

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9.1 GENERAL

This section of the Guidelines covers general information. Information specific to individual properties can be found in pertinent sections.

9.1.1 INTRODUCTION — Design properties in MIL-HDBK-5 are used in the design of aerospace structures and elements. Thus, it is exceedingly important that the values presented in MIL-HDBK-5 reflect as accurately as possible the actual properties of the products covered.

Throughout the Guidelines, many types of statistical computations are referenced. Since these may not be familiar to all who may be analyzing data in the preparation of MIL-HDBK-5 proposals, a detailed description of each operation is required. To present the detailed description in the individual sections, however, would unnecessarily complicate the orderly presentation of the overall computational procedures. Therefore, the detailed description of the statistical techniques have been covered in Section 9.6.

9.1.2 APPLICABILITY — Minimum data requirements and analytical procedures defined in these Guidelines for establishment of MIL-HDBK-5 design properties and elevated temperature curves for these properties should be used to obtain approval of such values or curves when proposed to the MIL-HDBK-5 Coordination Group or a certifying agency. However, the minimum data requirements and analytical procedures are not mandatory; to the extent of precluding use of other analytical procedures which can be substantiated. Any exceptions or deviations must be reported when requesting approval of these values or curves by the Coordination Group or certifying agency.

9.1.3 APPROVAL PROCEDURES — The MIL-HDBK-5 Coordination Group (a voluntary, joint Government-Industry activity) meets twice yearly. At each meeting, this group acts upon proposed changes or additions to the document submitted in writing in advance of the meeting. The agenda is normally mailed to attendees four weeks prior to the meeting date, and the minutes four weeks following the meeting. Attachments for either the agenda or the minutes should be delivered to the Secretariat well in advance of the mailing date.

Attachments containing proposed changes or additions to the document shall include specific notations of changes or additions to be made; adequate documentation of supporting data; analytical procedures used (see Section 9.1.4); discussion of analysis of data; and a listing of exceptions or deviations from the requirements of these Guidelines.

Approval procedures for establishment of MIL-HDBK-5 equivalent design values are defined by the individual certifying agency.

9.1.4 DOCUMENTATION REQUIREMENTS — The purpose of adequate documentation of proposals submitted to the MIL-HDBK-5 Coordination Group is to permit an independent evaluation of proposals by each interested attendee and to provide a historical record of actions of the Coordination Group. For this reason, both supporting data and a description of analytical procedures employed must be made available to attendees, either as an integral portion of an attachment to the agenda or minutes, or by reference to other documents that may reasonably be expected to be in the possession of MIL-HDBK-5 Meeting attendees. A specific example of the latter would be certain reports of Government-sponsored research or material evaluations for which distribution included the MIL-HDBK-5 attendance list. In some cases involving large quantities of supporting data, it may suffice (at the discretion of the Coordination Group) to furnish a single copy of these data to the Secretariat, from whom they would be available to interested attendees.

All relevant reference documents (specifications, testing standards, data submissions, etc.) for proposals must be provided in English, to facilitate interpretation and evaluation by the MIL-HDBK-5 Coordination Group. If metric units are used as the primary system of units in these documents, a soft conversion to English units must also be provided. The following English units are standard within MIL-HDBK-5:

- Coefficient of thermal expansion, 10^{-6} in./in./F
- Density, lb./in^3
- Fracture toughness, ksi-in$^{1/2}$
- Frequency, Hz (cycles per second), or cpm (cycles per minute)
- Load, lbs., or kips (10^3 lbs.)
- Modulus of elasticity (Tension and Compression), 10^3 ksi
- Shear Modulus, 10^3 ksi
- Specific heat, Btu/(lb.)(F)
- Strain, in./in.
- Stress or strength, ksi
- Temperature, F
- Thermal conductivity, Btu/[(hr)(ft^2)(F)/ft]
- Thickness, in.
- Time, hrs.

Refer to Section 9.2.2.2 for the terminology used within MIL-HDBK-5 for mechanical properties.

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9.1.5 SYMBOLS AND DEFINITIONS (also see Sections 9.2.2, 9.3.4.2, 9.3.6.2, 9.4.1.2, 9.5.1.2, and 9.6) —

α	—	Significance level; probability (risk) of erroneously rejecting the null hypothesis (see Section 9.6.2).
$\alpha_{99,90}$	—	Shape parameter estimates for a T_{99} or T_{90} tolerance bound based on an assumed three-parameter Weibull distribution.
α_{50}	—	Shape parameter estimate for the Anderson-Darling goodness-of-fit test based on an assumed three-parameter Weibull distribution.
A	—	A-basis for mechanical property (see Section 9.2.2.1).
AD	—	Anderson-Darling test statistic, computed in goodness-of-fit tests for normality or Weibullness.
$\beta_{99,90}$	—	Scale parameter estimate for a T_{99} or T_{90} tolerance bound based on an assumed three-parameter Weibull distribution.
β_{50}	—	Scale parameter estimate for the Anderson-Darling goodness-of-fit test based on an assumed three-parameter Weibull distribution.
B	—	B-basis for mechanical property (see Section 9.2.2.1).
df	—	Degrees of freedom.
F	—	The ratio of two sample variances.
heat	—	All material identifiable to a single molten metal source. (All material from a heat is considered to have the same composition. A heat may yield one or more ingots. A heat may be divided into several lots by subsequent processing.)
$k_{99,90}$	—	The T_{99} or T_{90} tolerance limit factor for the normal distribution, based on 95 percent confidence and a sample of size n.
log	—	Base 10 logarithm.
lot	—	All material from a heat or single molten metal source of the same product type having the same thickness or configuration, and fabricated as a unit under the same conditions. If the material is heat treated, a lot is the above material processed through the required heat-treating operations as a unit.
ln	—	Natural (base e) logarithm.
n	—	Number of individual measurements or pairs of measurements; Ramberg-Osgood parameter.
r	—	Ratio of two paired measurements; rank of test point within a sample.
$\bar{r}$	—	Average ratio of paired measurements.
S	—	S-basis for mechanical property values (see Section 9.2.2.1).
s	—	Estimated population standard deviation.
$\tau_{99,90}$	—	Threshold estimates for a T_{99} or T_{90} tolerance bound based on an assumed three-parameter Weibull distribution.
τ_{50}	—	Threshold estimate for the Anderson-Darling goodness-of-fit test based on an assumed three-parameter Weibull distribution.
t	—	Tolerance factor for the "t" distribution with the specified "confidence" and appropriate degrees of freedom.
T_{90}	—	Statistically based lower tolerance bound for a mechanical property such that at least 90 percent of the population is expected to exceed T_{90} with 95 percent confidence.
T_{99}	—	Statistically based lower tolerance bound for a mechanical property such that at least 99 percent of the population is expected to exceed T_{99} with 95 percent confidence.
$V_{99,90}$	—	The T_{99} or T_{90} tolerance limit factor for the three-parameter Weibull distribution, based on 95 percent confidence, a sample of size n, and a specified degree of upper tail censoring.
X_i	—	Value of an individual measurement.
$\bar{X}$	—	Average value of individual measurements.
Σ	—	The sum of.
$'$	—	Value determined by regression analysis.

9.1.6 DATA REQUIREMENTS FOR INCORPORATION OF A NEW PRODUCT INTO MIL-HDBK-5—This section specifies requirements for the incorporation of a new product into MIL-HDBK-5 on an S-basis (see Section 9.2.2.1 for definition). These requirements are applicable to each alloy, product form, and heat treat condition or temper. Sections 9.1.6.2 through 9.1.6.7 delineate requirements for a test program for the determination of mechanical property data suitable for computation of derived properties (see Section 9.2.10). A test matrix, based on these requirements, is shown in Table 9.1.6.

9.1.6.1 *Material Specification* — To be considered for inclusion in MIL-HDBK-5, a product must be covered by an industry specification (AMS specification issued by SAE Aerospace Materials Division or an ASTM standard published by the American Society for Testing and Materials), or a government specification (Military or Federal). If a public specification for the product is not available, action should be initiated to prepare a draft specification. Standard manufacturing procedures shall have been established for the fabrication and processing of production material before a draft specification is prepared. The draft specification shall describe a product which is commercially available on a production basis. An AMS draft specification should be submitted to the SAE Aerospace Materials Division and an ASTM standard should be transmitted to the American Society for Testing and Materials for publication. See Section 9.1.6.8 for requirements to substantiate the S-basis properties.

Foreign-produced materials not covered by a U.S. industry specification, but covered by an internationally recognized material specification may be considered for publication first in the Preliminary Material Properties (PMP) Handbook, which is a periodically updated MIL-HDBK-5 supplemental data source. This approach allows for the rapid initial review and publication of preliminary design properties on these materials, while the required U.S. industry specifications and standards are being developed and approved. Once the specifications are in place and other data requirements for introduction of these materials into MIL-HDBK-5 are satisfied, a proposal can be made to have the applicable data tables and curves transferred to MIL-HDBK-5.

9.1.6.2 *Material* — The product used for the determination of mechanical properties suitable for use in the determination of minimum design (derived) values for incorporation into MIL-HDBK-5 shall be production material. The material shall have been produced using production facilities and standard fabrication and processing procedures. If a test program to determine requisite mechanical properties is initiated before a public specification describing this product is available, precautionary measures shall be taken to ensure that the product supplied for the test program conforms to the specification, when published, and represents production material.

Ten lots of material from at least three production heats, casts or melts for each product form and heat treat condition shall be tested to determine required mechanical properties. See Table 9.1.6.2 for definitions of heat, cast, and melt. A lot is defined as all material of a specific chemical composition, heat treat condition or temper, and product form which has been processed at the same time through all processing operations. Different sizes and configurations from a heat cast or melt shall be considered different lots. For a single lot of material, only one heat treat lot may be used to meet the ten-lot requirement. Thicknesses of the 10 lots to be tested shall span the thickness range of the product form covered by the material specification (or for the thickness range for which design values are to be established).

Dimensionally discrepant castings or special test configurations may be used for the development of derived properties with prior approval by the MIL-HDBK-5 Coordination Group, providing these castings meet the requirements of the applicable material specification. Design values for separately cast test specimens shall not be presented in MIL-HDBK-5.

9.1.6.3 *Test Specimens* — Mechanical property ratios are utilized in the analysis of data to determine minimum design values. Tensile yield in other than primary test direction, compressive yield, and bearing yield strengths are paired with the tensile yield strength in the primary test direction for each lot. Tensile ultimate in other than the primary test direction, shear ultimate, and bearing ultimate strengths are paired with the tensile ultimate strength in the primary test direction. See Table 9.2.10 for the primary testing direction for various products. Therefore, it is imperative that these test specimens be taken from the same sheet, plate, bar, extrusion, forging, or casting. Test specimens shall be located in close proximity. If coupons or specimens are machined prior to heat treatment, all specimens representing a lot shall be heat treated simultaneously in the same heat treat load through all heat treating operations. This procedure is necessary to provide precise mechanical property relationships (ratios).

Test specimens shall be located within the cross section of the product in accordance with the applicable material specification, or applicable sampling specification, such as AMS 2355, AMS 2370, and AMS 2371. Subsize tensile and compressive test specimens may be used when appropriate. Specimen drawings should be provided along with each data proposal, with English units included. The applicable testing standard should be identified along with the specimen drawings. If the standard is not routinely available in English, an English translation of the standard should be provided.

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Table 9.1.6. Test Matrix to Provide Required Mechanical Property Data for Determination of Design Values for Derived Properties (on S-Basis)

Lot Letter[a,b,c]	Test Specimen Requirements												
	TUS & TYS[d,e,f,g]			CYS[d,e,g]			SUS[h]			BUS & BYS[i], e/D = 1.5		BUS & BYS[i], e/D = 2.0	
	L	LT	ST[j]	L	LT	ST[j]	L	LT	ST[j]	L	LT[j]	L	LT[j]
A	2[k]	2	2	2	2	2	2	2	2	2	2	2	2
B	2	2	2	2	2	2	2	2	2	2	2	2	2
C	2	2	2	2	2	2	2	2	2	2	2	2	2
D	2	2	2	2	2	2	2	2	2	2	2	2	2
E	2	2	2	2	2	2	2	2	2	2	2	2	2
F	2	2	2	2	2	2	2	2	2	2	2	2	2
G	2	2	2	2	2	2	2	2	2	2	2	2	2
H	2	2	2	2	2	2	2	2	2	2	2	2	2
I	2	2	2	2	2	2	2	2	2	2	2	2	2
J	2	2	2	2	2	2	2	2	2	2	2	2	2

a Ten lots, representing at least three production heats, or casts or melts, are required.
b Thicknesses of ten lots shall span thickness range of product form covered by material specification.
c For a single lot, multiple heat treat lots shall not be used to meet 10-lot requirement.
d If precision modulus values for E and E_c are not available, precision modulus tests should be conducted on three lots.
e Stress-strain data from at least three lots shall be submitted.
f Full-range tensile stress-strain data from at least one lot shall be submitted, but data from three or more lots are preferred.
g Products should also be tested in the 45° grain direction that are anticipated to have significantly different properties in this direction than the standard grain directions; these include materials such as aluminum-lithium alloys and Aramid fiber reinforced sheet laminate.
h It is recommended that sheet and strip ≥0.050 inch in thickness be selected for shear tests conducted according to ASTM B 831. Shear testing of sheet <0.050 inch in thickness may result in invalid results due to buckling around the pin hole areas during testing.
i It is recommended that minimum sheet and strip selected for bearing tests comply with the t/D ratio (0.25-0.50) specified in ASTM E 238. For failure modes, see Figure 9.4.1.7.2.
j As applicable, depending on product form and size.
k At least two specimens are recommended; however, a single test is acceptable if retesting can be accomplished to replace invalid tests.

Supersedes page 9-8 of MIL-HDBK-5H

Table 9.1.6.2. Definitions of Heat, Melt, and Cast

Material	Heat, Melt, or Cast
Ingot Metallurgy Wrought Products Excluding Aluminum Alloys	A heat is material which, in the case of batch melting, is cast at the same time from the same furnace and is identified with the same heat number; or, in the case of continuous melting, is poured without interruption.
Ingot Metallurgy Wrought Aluminum Alloy Products	A cast consists of the sequential aluminum ingots which are melted from a single furnace charge and poured in one or more drops without changes in the processing parameters. (The cast number is for internal identification and is not reported.)
Powder Metallurgy Wrought Products Including Metal-Matrix Composites	A heat is a consolidated (vacuum hot pressed) billet having a distinct chemical composition.
Cast Alloy Products Including Metal-Matrix Composites	A melt is a single homogeneous batch of molten metal for which all processing has been completed and the temperature has been adjusted and made ready to pour castings. (For metal-matrix composites, the molten metal includes unmelted reinforcements such as particles, fibers, or whiskers.)

Test specimens shall be excised in longitudinal, long transverse, and short transverse (when applicable) grain directions. Mechanical properties shall also be obtained in the 45° grain direction for materials that are anticipated to have significantly different properties in this direction than the standard grain directions. For some product configurations, it may be impractical to obtain transverse bearing specimens. For aluminum die forgings, the longitudinal grain direction is defined as orientations parallel, within ±15°, to the predominate grain flow. The long transverse grain direction is defined as perpendicular, within ±15°, to the longitudinal (predominate) grain direction and parallel, within ±15°, to the parting plane. (Both conditions must be met.) The short transverse grain direction is defined as perpendicular, within ±15°, to the longitudinal (predominate) grain direction and perpendicular, within ±15°, to the parting plane. (Both conditions must be met.) All three grain directions are applicable and tests shall be conducted.

Triplicate test specimens are preferred. Single test specimens may be acceptable for some products providing retesting can be performed when needed. Duplicate specimens are recommended as an economical compromise. Some variation in strength within a product is expected. The use of replicate specimens provides multiple mechanical property observations so that lot averages can be used to form paired mechanical property ratios. Mechanical property ratios formed from lot averages are more reliable than those formed from individual observations.

9.1.6.4 ***Test Procedures*** — All tests shall be performed in accordance with applicable ASTM specifications, or their equivalent. The pin shear testing of aluminum alloys should be done in conformance to ASTM B 769, or an equivalent public specification. Grain orientations and loading directions for shear specimens must be defined in accordance with ASTM B 769, or an equivalent specification. Shear testing standards are not available in the U.S. for aluminum alloy sheet, strip, or thin extrusions or for products from other alloy systems. Bearing tests for products from all alloy systems shall be conducted in accordance with ASTM E 238, or an equivalent public specification, using "clean pin" test procedures. For aluminum alloy plate, bearing specimens are oriented flatwise and for aluminum alloy die and hand forgings, bearing specimens must be oriented edgewise, as described in Section 3.1.2.1.1.

9.1.6.5 ***Mechanical Properties*** — Tensile, compression, shear, and bearing tests shall be conducted at room temperature to determine tensile yield and ultimate strengths, compressive yield strength, shear ultimate strength, and bearing yield and ultimate strengths for e/D = 1.5 and e/D = 2.0 for each grain direction and each lot of material. All data shall be identified by lot, or heat, or melt. For materials used exclusively in high temperature applications, such as gas turbine or rocket engines, the determination of design values for compression, shear, and bearing strengths may be waived by the MIL-HDBK-5 Coordination Group. In lieu of data for these properties, sufficient elevated temperature data for tensile yield and ultimate strengths, as well as modulus of elasticity, shall be submitted so that elevated temperature curves can be constructed. Data should be submitted for the useful temperature range of the product. See Section 9.3.1.1.1 for data requirements for elevated temperature curves.

9.1.6.6 ***Modulus of Elasticity Data*** — Tensile and compressive modulus of elasticity values shall be determined for at least three lots of material. Elastic modulus values are those obtained using a Class B-1 or better extensometer. The method of determining or verifying the classification of extensometers is identified in ASTM E 83. ASTM E 111 is the standard test method for the determination of Young's Modulus, tangent modulus, and chord modulus of structural materials. A modulus value shall also be obtained for the 45 degree grain orientation for materials that are anticipated to have significantly different properties in this direction than the standard grain directions.

9.1.6.7 *Other Data* — Room temperature, tensile, and compressive load-deformation curves or stress-strain data for each grain direction from at least three lots shall be provided. Room temperature, full-range, tensile load deformation curves or stress-strain data for each grain direction shall also be provided. Full-range stress-strain data shall be provided for at least one lot, but data for three lots are preferable. For heat resistant materials for which elevated temperature data for tensile yield and ultimate strengths are required, room and elevated temperature stress-strain data shall be provided. A precise density value in pounds per cubic inch shall be provided. Although not required, physical property data for coefficient of expansion, thermal conductivity, and specific heat should be submitted, when available. Also, information regarding manufacturing (fabrication and processing), environmental effects (corrosion resistance), heat treat condition and applicable specification shall be provided so that a comments and properties section can be prepared. Also, data for creep, stress rupture, fatigue crack propagation, fatigue and fracture toughness properties should be submitted whenever possible, especially when applicable specifications contain minimum property requirements, such as minimum fracture toughness values.

9.1.6.8 *Guideline Requirements for Specification Minimum Design Mechanical Properties* (S-basis) — A product must be covered by an industry specification prior to being considered for inclusion into MIL-HDBK-5 as indicated in 9.1.6.1. Within a specification, one of the basic requirements is to provide minimum properties (S-basis) which includes tension yield, tension ultimate, elongation and compression yield (when specified). As indicated in Section 9.2.2, the statistical significance to the S-basis properties is typically not known. However, it is known that minimum mechanical properties in the SAE/AMS specifications have been statistically justified in recent years (since ~ 1975) with a procedure contained in their documents. With that in mind, a procedure has been established to provide some level of statistical significance to these S-basis properties contained within the Handbook.

A material being submitted for inclusion into MIL-HDBK-5 shall include as part of the substantiation package the basis of the specification properties. This substantiation package should include the number of test samples, the number of lots, and the method of determining any property covered in the specification even if it is not to be reported in MIL-HDBK-5. This could include the development of minimum as well as maximum properties. Consideration must be made for the specified sizes, product forms, heat treatments and other variables affecting the physical and mechanical properties. It is also expected that the test material chemistry be in the nominal specification range and not tailored to the chemistry extremes.

It is recommended that the substantiation be based on a procedure similar to SAE/AMS in which the analysis of data or other appropriate documentation supports a statistical S-basis value where at least 99 percent of the population of values is expected to equal or exceed the minimum value with a confidence of 95 percent. Since only limited quantities of data are generally available for the basic mechanical properties (tension yield, tension ultimate, compression yield), it is recommended that at least 30 test samples from at least three heats or lots of material are provided for each thickness range or product form. The S-basis value may be computed by assuming the distribution of the sample population to be normal and using the following equation:

$$\text{Minimum S} = \bar{X} - s \cdot k_{99} \tag{9.1.6.8}$$

where

$\bar{X}$	=	sample mean
s	=	standard deviation
k_{99}	=	one-sided tolerance-limit factor corresponding to a proportion at least 0.99 of a normal distribution and a confidence coefficient of 0.95 based on the number of specimens (See Table 9.6.4.1).

All data analyses must to be performed in English units. Strength data recorded in metric units should be converted to English units, to the nearest 0.01 ksi, before data analyses are undertaken. If desired by the data supplier, metric equivalent tables and figures can be included as part of the working data submitted with a data proposal, but the tables and/or figures proposed for inclusion in MIL-HDBK-5 will contain only English units.

When the tensile and compressive properties vary significantly with thickness, regression analysis should be used.

Although the establishment of an S-basis value should be based upon the statistically computed value, the S-basis value may be slightly lower, based on experience and judgement, to insure conservative values.

9.1.7 PROCEDURE FOR THE SUBMISSION OF MECHANICAL PROPERTY DATA — This section specifies the procedure for submission of mechanical property data for statistical analysis; specifically data supplied for the determination of T_{99} and T_{90} values for F_{tu} and F_{ty} and for data supplied to obtain derived property values for F_{cy}, F_{su}, F_{bru} and F_{bry}. The amount of data to be supplied for both of these are indicated in other sections of Chapter 9, such as Table 9.1.6 for derived property values. This section covers the format to submit the data in electronic form.

9.1.7.1 *Computer Software* — The data can be supplied on 3.5 inch disks for PC format or sent electronically. It is recommended that the software applications in Table 9.1.7.1 be used to construct the data files. Along with the floppy disk, provide a hard (paper) copy of the data contained on the disk and any other supporting documentation such as specimen dimensions, gage length etc. This information will be stored in the MIL-HDBK-5 archives for future reference.

Table 9.1.7.1. Software Applications for Data Submission

ASCII text editor
- Current Spreadsheet or Database Applications
- The Chairman or Secretary of MIL-HDBK-5 can be contacted concerning software compatibility questions.

The data supplied on these disks are to be supplied in English units. For example, physical dimensions should be reported in units of inches to the nearest thousandth of an inch (X.XXX), stress should be reported in units of ksi to the nearest one hundredth of a ksi (X.XX), strain is to be reported in percent to the nearest tenth of a percent (X.X) and modulus is to be reported in units of 10^3 ksi to the nearest tenth of a msi (X.X). If necessary, refer to Table 1.2.2 to convert to English units of measure.

9.1.7.2 *General Data Format* — Tables 9.1.7.2(a) and (b), for wrought and cast products respectively, show the information that should be supplied in electronic form along with the mechanical test results. The columns (or data fields), in order, will contain alloy type, specification number, temper/heat treatment, lot and/or heat number, product form, product thickness, specimen location, grain direction, and specimen number. Columns will be added towards the right of the specimen number and will contain the individual test results as discussed in Sections 9.1.7.3 and 9.1.7.4.

When specifying grain direction for wrought product strengths, etc., use the conventions identified in Table 9.1.6: L for longitudinal, LT for long transverse, and ST for short transverse. Products that are anticipated to have significantly different properties in directions other than those stated above should be tested in the appropriate directions and the results reported.

There are several types of product forms identified in the Handbook; therefore, the term product form should be properly defined and reported in this column. Examples for wrought products are sheet, plate, bar, and forging. Examples for cast products are sand casting , investment casting, and permanent mold casting. For cast products it is important to identify properties from designated or nondesignated areas.

9.1.7.3 ***Data Format for the Determination of A and B-Basis Values of F_{tu} and F_{ty}*** — The tensile test results that are to be reported for determination of A and B-basis properties are tensile ultimate strength (TUS), tensile yield strength (TYS), elongation (e), reduction of area (RA), and modulus. The results of these tests are to be reported as shown in Table 9.1.7.3 along with alloy designation, specification, lot and/or heat number, product thickness, grain direction, etc. as previously shown in Table 9.1.7.2. The number of tests required for determining A and B-basis properties are identified in Section 9.2.

9.1.7.4 ***Data Format for Derived Property Values*** — For the derived property values, several types of tests may be conducted such as tensile, compression, shear and bearing, as shown in Table 9.1.6. The results of these tests are to be reported as shown in Table 9.1.7.4 along with alloy designation, specification, lot and/or heat number, product thickness, grain direction, etc. as previously shown in Table 9.1.7.2. The ultimate strength properties are to be contained in one file as shown in Table 9.1.7.4(a) while the yield strength properties are to be contained in another file as shown in Table 9.1.7.4(b).

Generally, two tests are preferred (one required) for a given test type and product thickness. The results of these tests are to be reported in columns adjacent to each other. For example, TUS Test #1 and TUS Test #2 are on the same row for a given thickness and heat. An additional column should be created to report the specimen number for the second test. This column should be just to the left of the test result. The same procedure is to be used for the other properties. The abbreviations (see Section 1.2.2) for the other test types are CYS for compressive yield, SUS for shear ultimate, and BUS and BYS for bearing ultimate and bearing yield strengths, respectively. For the bearing properties, also identify the e/D ratio of either 1.5 or 2.0.

9.1.7.5 ***Data Format for the Construction of Typical Stress-Strain Curves*** — The tensile and compression stress-strain data should also be submitted in electronic form, if possible, so that typical tensile and compression stress-strain curves, compression tangent-modulus and typical tensile (full-range) curves can be constructed. In order to construct a typical stress-strain curve, the individual specimen curves must be documented up to slightly beyond the 0.2 percent offset yield strength. To construct a typical (full-range) stress-strain curve, the individual curves must be documented through to failure.

The data for the stress-strain curves must be supplied on a separate floppy disk from the mechanical property data. The data should be stored in a file which contains the load (or stress) in the first column and the displacement (or strain) in the second column. Each stress-strain pair should be identified with its corresponding specimen identification number.

For the load-displacement curves, the load should be reported in pounds (X.) and the displacement should be reported in units of thousandth of an inch (X.XXX). For stress-strain curves, the stress should be reported to the nearest hundredth of a ksi (X.XX) and strain should be reported to the nearest X.XX $\times 10^{-6}$ units.

A hard copy of the load displacement curve should also be submitted for each stress-strain curve.

Table 9.1.7.2(a). General Data Format for Wrought Products

Alloy Trade Name	Industry/ Government Specification No.	Temper/Heat Treatment	Lot and/or Heat No.	Product Form	Product Thickness (in.), or Area (in.^{2})	Speci-men Location	Grain Direc-tion	Specimen No.

Table 9.1.7.2(b). General Data Format for Cast Products

Alloy Trade Name	Industry/ Government Specification No.	Temper/Heat Treatment	Lot and/or Heat No.	Product Form	Product Thickness	Specimen Location (Designated, Nondesig-nated)	Specimen No.

Table 9.1.7.4(b). Derived Yield Properties

Alloy Trade Name		Specimen No.	TYS Test 1	TYS Test 2*	CYS Test 1	CYS Test 2*	BYS e/D=1.5 Test 1	BYS e/D=1.5 Test 2*	BYS e/D-2.0 Test 1	BYS e/D=2.0 Test 2*
	The information to be entered between these two									
	columns depends upon the product form, see Table 9.1.7.2(a) or (b).									

* Two tests are preferred, only one is required.

9.2 ROOM-TEMPERATURE DESIGN PROPERTIES

9.2.1 INTRODUCTION — This section contains detailed procedures for the determination of room-temperature design properties.

9.2.2 DESIGNATIONS AND SYMBOLS — Designations and Symbols presented in this section are applicable throughout the MIL-HDBK-5, but are particularly pertinent to computation and presentation of room-temperature mechanical properties.

9.2.2.1 *Data Basis* — There are four types of room-temperature mechanical properties included in MIL-HDBK-5. They are listed here, in order, from the least statistical confidence to the highest statistical confidence, as follows:

Typical Basis — A typical property value is an average value and has no statistical assurance associated with it.

S-Basis — This designation represents the specification minimum value specified by the governing industry specification (as issued by standardization groups such as SAE Aerospace Materials Division, ASTM, etc.) or federal or military standards for the material. (See MIL-STD-970 for order of preference of specifications.) For certain products heat treated by the user (for example, steels hardened and tempered to a designated F_{tu}), the S-basis value may reflect a specified quality-control requirement. Traditionally, the statistical assurance of S-basis values has not been known. However, the statistical assurance associated with S-basis values established since 1975 is known within the limitations of the qualification sample and the analysis method used to evaluate the data. Within those constraints S-basis values established since 1975 may be viewed as estimated A-basis values.

Wherever possible, the statistical validity of these estimated A-basis (S-basis) values should be verified as soon as sufficient heats and lots of material are available from the major producers to establish more rigorous A-basis properties by the methods described in MIL-HDBK-5. If the more rigorous A-basis property exceeds the S-basis value, the major suppliers and users of the material may benefit from updating or replacing the specification because then they will be able to take full advantage of the capabilities of the material within the design allowable tables in MIL-HDBK-5.

In the opposite (and fortunately infrequent) situation where the more rigorous A-basis property falls well below the S-basis value, the repercussions may be greater for both the user and producer. Actual design margins (as compared to originally perceived design margins) on primary structure may be reduced below desirable levels if the S-basis value must be downgraded to a lower A-basis value. The perceived adequacy of a material for a particular application may be reduced if the S-basis value is reduced to match a lower A-basis value. However, under most circumstances, the S-basis value should be reduced to match the A-basis value if process improvements cannot be instituted to raise the A-basis value to the level of the original S-basis value.

B-Basis — This designation indicates that at least 90 percent of the population of values is expected to equal or exceed the statistically calculated mechanical property value, with a confidence of 95 percent. This statistically calculated number is computed using the procedures specified in Section 9.2.

A-Basis — The lower value of either a statistically calculated number, or the specification minimum (S-basis). The statistically calculated number indicates that at least 99 percent of the population is expected to equal or exceed the statistically calculated mechanical property value with a confidence of 95 percent. This statistically calculated number is computed using the procedures specified in Section 9.2.

Sections 9.2.5, 9.2.7.1, 9.2.8.1, and 9.2.9.1 contain discussions of data requirements for direct computation of design properties based on current process capability of the majority of suppliers of a given material and product form. To assure that the A- and B-basis values, defined above, represent true current process capability of a material, all available original test data for current material that is produced and supplied to the appropriate government, industry, or equivalent company specifications are included in calculating these values. (However, to be considered for inclusion in MIL-HDBK-5, a material must be covered by an industry, Federal, or Military specification per Section 9.1.6.) Only positive proof of improper processing or testing is cause for exclusion of original test data, except that the number of tests per lot shall not exceed the usual frequency of testing for the product. It is recognized, however, that extensive acceptance testing resulting in elimination of low-strength material from the population may justify establishment of higher mechanical-property values for the remaining material. Since this is a function of both the type of product and the nature and frequency of the acceptance tests practiced by each company, it is impractical to attempt to include these considerations in this document.

Usually, only tensile ultimate and yield strengths in a specified testing direction are determined in such a manner that they can be termed A- and B-basis values, in accordance with definitions given above. Only tensile ultimate strength, tensile yield strength, elongation, and reduction of area (for some alloys) are normally specified in the governing specifications and can be termed S-basis values. However, ratioing procedures (described in Section 9.2.10) have been established, by which other property values such as

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(2) Each remaining data set should be tested for acceptability using the three-parameter Weibull acceptability test described in Section 9.2.4.2. If there is statistical evidence that one or more statistically distinct data sets do not meet the specification minimum value, the results will be brought to the Material Data Review Working Group where a decision will be made on whether or not these data sets should be included in the computation of material property values.

(3) All remaining data sets should be tested for homogeneity using the k-sample Anderson-Darling test. If the data sets are found to be homogeneous, T_{99} and T_{90} values can be calculated using a single combined data set. If the populations are not homogeneous, material property values must be determined by calculating T_{99} and T_{90} values for each data set.

9.2.4.2 *Three-Parameter Weibull Acceptability Test* — The three-parameter Weibull acceptability test is designed to determine whether an acceptable proportion of a producer's population is likely to exceed the specification limit for corresponding material property. To carry out this test, an upper confidence bound (UCB) is calculated for the first percentile of the producer's population assuming that the population is distributed according to a three-parameter Weibull distribution. This UCB value is calculated in the same manner as a T_{99} value is calculated (in Section 9.2.8) with the following modifications:

(1) In solving for the threshold $\tau(\theta)$ (Section 9.6.5.1), θ should be set equal to 0.10.

(2) The value of V_{99} should be taken from Table 9.6.4.7 rather than Table 9.6.4.8 when using the formula for T_{99} (Equation [9.2.8.2,(e)]) to calculate the UCB value.

If UCB is greater than or equal to the specification limit, it is concluded that the producer's data is acceptable. If UCB is less than the specification limit, it is concluded (with a 5 percent risk of error) that the producer's data do not meet the specification minimum value.

In statistical terms, this method tests (at 5 percent significance level) the hypothesis that at least 99 percent of the producer's population is greater than the specification limit. If the hypothesis is not rejected (UCB greater than or equal to specification limit), then it is concluded that the producer's data is acceptable. If the hypothesis is rejected (UCB less than the specification limit), it is concluded that the producer's data is unacceptable.

This technique is applicable only when data have not been censored from the sample. It also assumes that the data are distributed according to a three-parameter Weibull distribution (although normally distributed data are also accommodated by this test). If the data sample is highly skewed, background data should be reviewed to determine whether the skewness is caused by a mixed population. If it is not, the Weibull test procedure can be applied. This test should be applied to both tensile yield and ultimate strengths (in appropriate grain directions), and if a producer's data is unacceptable for either property, that producer's data for both properties should be excluded for the purpose of computing T_{99} and T_{90} values.

9.2.5 DECIDING BETWEEN DIRECT AND INDIRECT COMPUTATION — The only room-temperature design properties that are regularly determined by direct computation are F_{tu} and F_{ty}. This procedure is usually limited to a specified or usual testing direction because there are seldom enough data available to determine properties in other test directions. Two rules govern the choice between direct and indirect computation:

(1) F_{tu} and F_{ty} in the specified or usual testing direction may be determined by direct computation only.

(2) F_{tu} and F_{ty} in other testing directions (as well as F_{cy}, F_{su}, F_{bru}, and F_{bry} in all directions) may be determined by direct computation only if (a) the data are adequate to determine the distribution form and reliable estimates of population parameters, or (b) the sample includes 300 or more individual, representative observations of the property to be determined.

For example, assume that available data for a relatively new alloy comprise 50 observations of TUS in the specified testing direction. This sample is not considered large enough to determine the distribution form and reliable estimates of population mean and standard deviation. Since only direct computation is permitted in this instance, determination of T_{99} and T_{90} values must be postponed until a larger sample is available. However, these properties may be considered for presentation on the S basis at the discretion of the MIL-HDBK-5 Coordination Group, contingent on availability of an acceptable procurement specification for the material.

If the number of observations increases to 100, this quantity may be adequate to allow determination of T_{99} and T_{90}-values, provided data can be described by a Pearson Type III (gamma) or Weibull distribution. If the distribution cannot be described parametrically, at least 299 observations are required so that computation can proceed without knowledge of the distributional form.

If the above example involved observations of SUS instead of TUS, the same criteria would apply for direct computation. However, F_{su} could be determined by indirect computation with as few as ten paired observations of SUS and TUS (representing at least ten lots and two heats), provided F_{tu} has been established.

9.2.6 DETERMINING THE APPROPRIATE COMPUTATION PROCEDURE

9.2.6.1 ***Background*** — Prior to 1984, lower tolerance bound mechanical properties (T_{99}, T_{90}) were established by one of two methods. If the sample population was found to be normally distributed by a chi-square test, then standard normal distribution computation procedures were used. Otherwise, non-parametric procedures were used.

In 1984, use of the normal distribution was supplemented by use of the three-parameter Weibull distribution to accommodate skewness in material properties. In addition, the chi-square test was replaced by the more sensitive Anderson-Darling goodness-of-fit test. Because the Anderson-Darling test is especially sensitive to departures in the tails from the candidate distribution (the very high and very low observations) in many situations, the Weibull distribution is often rejected, even when the model fit (by a probability plot) appears adequate in the lower values.

To permit computation of lower tolerance bounds in more of these cases, the Weibull approach was expanded to incorporate two different levels of upper-tail censoring and a last-resort conservative "backoff" option. Also, a modified version of the A-D test was developed which places more emphasis on the lower tail than the upper tail.

During the development of the Weibull procedure (Section 9.2.8), it became evident how inadequate the traditional normal procedure is for computing tolerance bounds when the data come from a skewed distribution – even if a goodness-of-fit test is applied to screen out non-normal distributions. Table 9.2.6.1 illustrates the shortcomings of the normal procedure for computing T_{99} and T_{90} for distributions[1] ranging in skewness from minus 1 to plus 1. The second column provides estimates of the probability that a sample of size 100 will be "accepted" as normal. Notice that for very skewed Weibull distributions, the proportion

[1] Table 9.2.6.1 is based on data generated from Weibull distributions with varying skewness. All distributions are standardized to a mean of 100 and standard deviation of 5.0.

accepted by the normal Anderson-Darling test is small, but it increases for distributions with skewness near zero.

The third column of Table 9.2.6.1 estimates the coverage, which is the probability (or confidence) that the method will yield a T_{99} below the true first percentile. This should be 95 percent. If the distribution is negatively skewed then the coverage can be substantially lower than the claimed 95 percent. The fourth column estimates the systematic bias of the procedure. Bias for T_{99} represents the difference between the 95th percentile of the T_{99} values produced by the normal procedure minus the true first percentile. (Bias is presented in units of standard deviations. This can be converted to, say, ksi units, if the standard deviation is known.) It can be interpreted as the amount that would have to be subtracted from the T_{99} values produced by the procedure to get an appropriate answer. The problem is, in practice, one never knows true skewness. Notice that as bias goes up, coverage goes down. The last two columns provide coverage and bias estimates for T_{90}. Although still significant, the errors associated with T_{90} are much smaller than those for T_{99}. Figure 9.2.6.1 displays the bias of T_{90} and T_{99} for skewness between minus1 and plus 1 (again, in units of standard deviations).

Normal-based methods can be very good for estimating the mean of a distribution - which is not very sensitive to skewness. However, in MIL-HDBK-5, much of the emphasis is on estimating the first and tenth percentiles - which are very sensitive to skewness. Table 9.2.6.1 and Figure 9.2.6.1 are provided to emphasize the notion that applying the normal method can result in very poor tolerance bound estimates due to undetected skewness. It is for this reason that the traditional normal method for computing tolerance bounds is not provided in the Handbook as a recommended procedure.

On the other hand, because methods based on the Weibull distribution are computationally intensive and have less intuitive appeal than methods based on the normal distribution, an alternative procedure was developed based on the Pearson Type III family of distributions. The Pearson family includes the normal distribution as a special case. The Pearson method was incorporated into the Guidelines in 1999.

The sequential Weibull procedure and the sequential Pearson procedure were developed based on distributions with skewness between minus 1 and 1. Therefore, the Weibull and Pearson procedures should not be applied if the sample skewness is outside this range. If no systematic effects (e.g., thickness) are identified as significant by regression, then only the nonparametric method (9.2.9) should be applied.

9.2.6.2 ***Computation Procedures*** — Current analysis procedures for computing lower tolerance bounds (T_{90}, T_{99}) are described in Figure 9.2.6(a). Three methods are permitted: the sequential Weibull procedure, the sequential Pearson procedure, and the nonparametric procedure. The remainder of this section provides an overview and a roadmap to these procedures. Figure 9.2.6(b) describes the procedure for translating T_{99} and T_{90} values to A and B values, and values for publication in the mechanical property tables in this Handbook.

Table 9.2.6.1. Performance of Normal Method for Calculating T_{90} and T_{99} on Samples of Varying Skewness

Skewness	Percent Accepted	T_{99} Percent Coverage	T_{99} Bias (Std. Dev.)	T_{90} Percent Coverage	T_{90} Bias (Std. Dev.)
-1.00	16	3	1.0	66	0.22
-0.75	40	11	0.7	78	0.16
-0.50	68	43	0.4	83	0.12
-0.25	91	82	0.2	88	0.08
0.00	98	98	-0.1	93	0.04
0.25	91	100	-0.4	97	-0.02
0.50	65	100	-0.6	99	-0.06
0.75	21	100	-0.7	100	-0.06
1.00	4	100	-0.7	100	-0.10

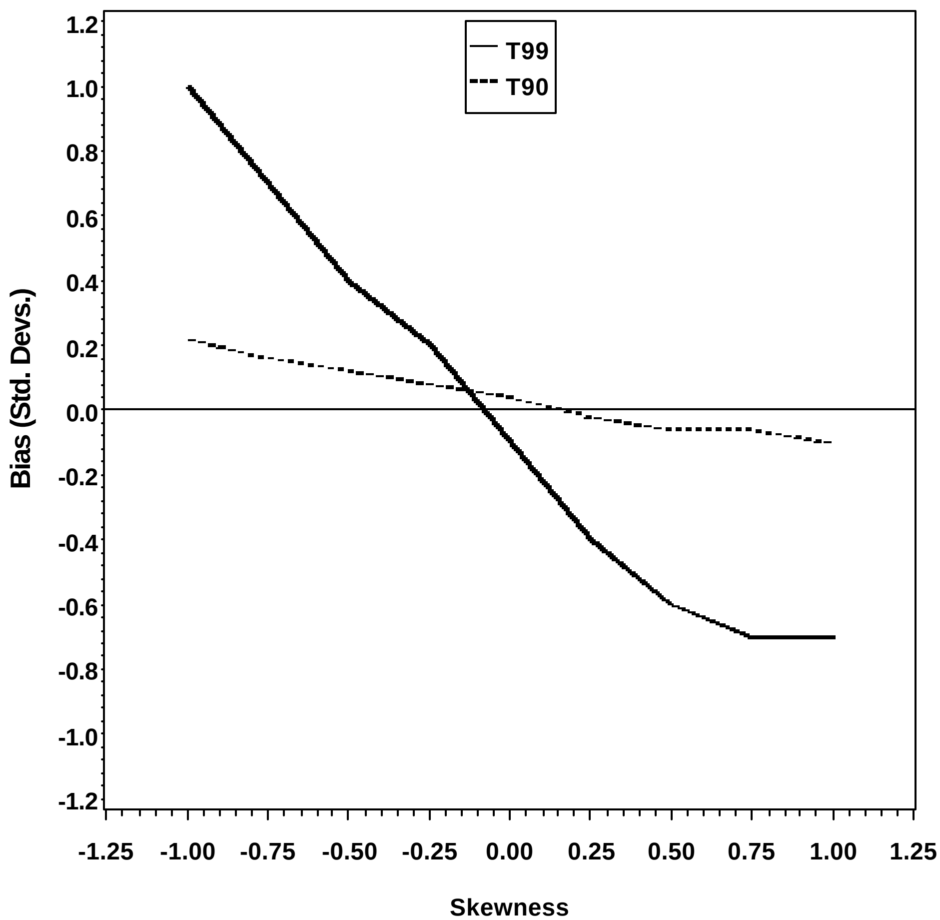

Figure 9.2.6.1. Estimated Bias of T_{99} and T_{90} Using Normal Method on Skewed Data.

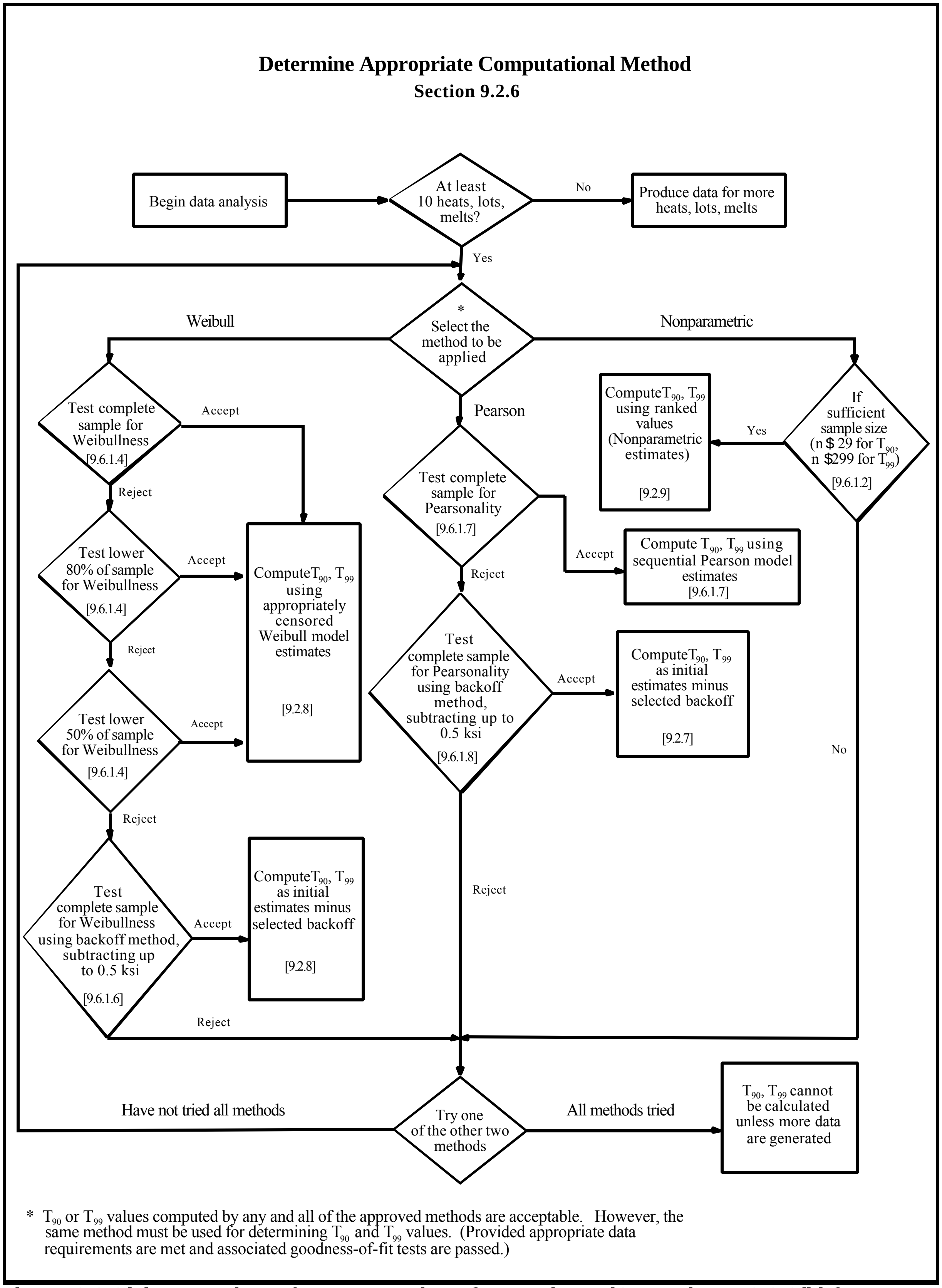

Figure 9.2.6(a). Procedures for computation of T_{99} and T_{90}. (Go to Figure 9.2.6(b) for guidance on conversion of T_{99} and T_{90} values to A and B values.)

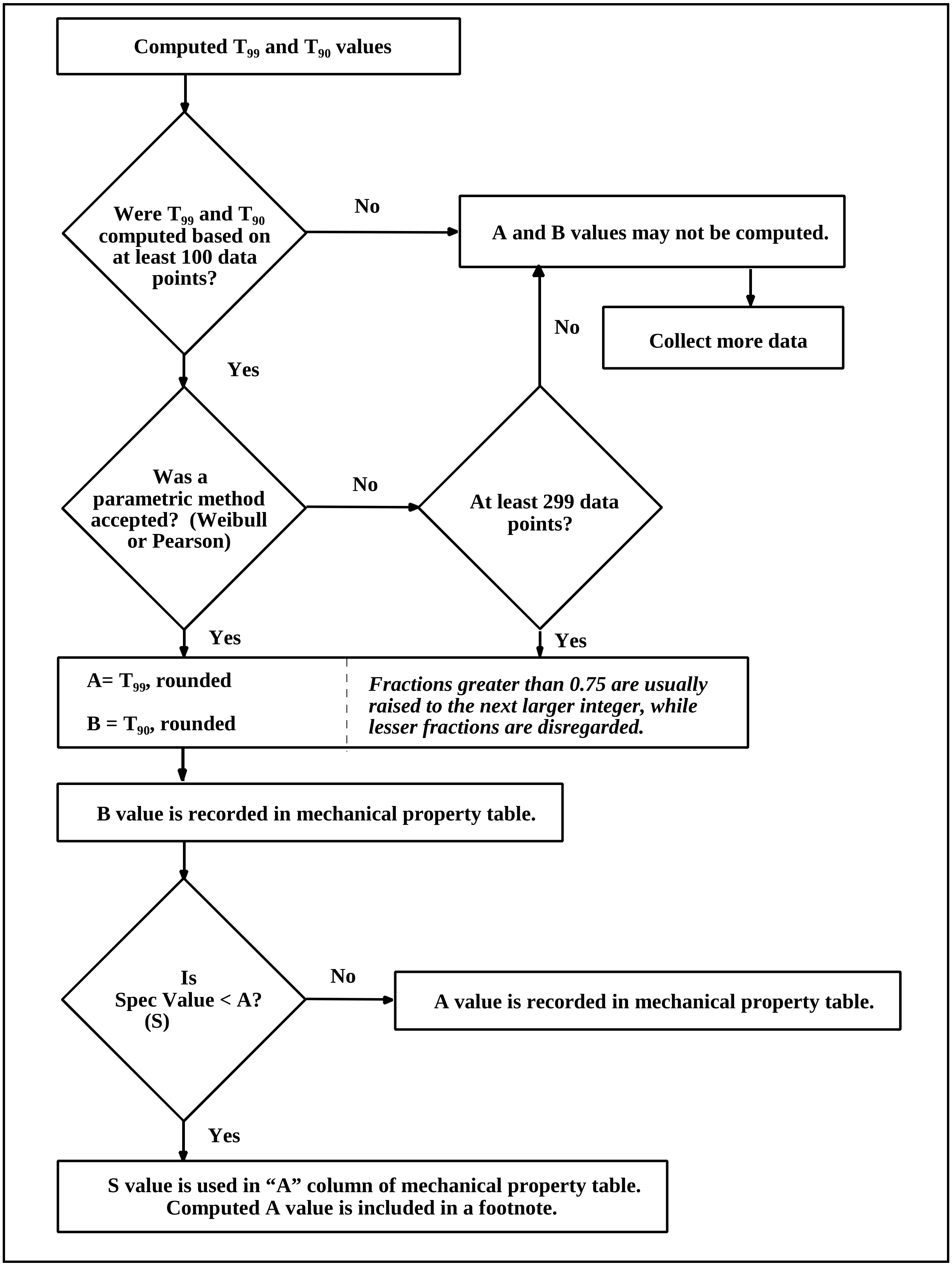

Figure 9.2.6(b). Procedure for Converting T_{99} and T_{90} values [from Figure 9.2.6(a)] to A and B Values, and Mechanical Property Table Values.

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In what follows, certain procedures require artificial censoring of the measured data. That is, because the real engineering interest for design lies in lower percentiles of the distribution of a material's properties, some of the following procedures ignore a portion of the observations in the upper tail. Specifically, we use the notation $X_{(1)} \leq X_{(2)} \leq \ldots \leq X_{(n)}$ to denote the ordered sample, and will frequently refer to the censored sample:

$$X_{(1)} \leq X_{(2)} \leq \ldots \leq X_{(r)},$$

where r/n represents the proportion of the sample which is uncensored. Alternatively, (1-r/n) represents the proportion of the sample which is censored. The terms r and n will be used throughout subsequent sections without redefinition. In the case of uncensored data, r=n.

When the sequential Weibull procedure is applied, a modified Anderson-Darling goodness-of-fit-test is conducted as described in 9.6.1.4 for the uncensored sample. If the assumption of Weibullness is not rejected, the lower tolerance bound should be computed using methods described in Section 9.2.8 for complete samples. (The risk that one may conclude erroneously that a true Weibull distribution is non-Weibull is set at 5 percent.) If the assumption of Weibullness is rejected for the complete sample, then the next step is to test the lower 80 percent of the data for Weibullness by trimming the top 20 percent of the measurements and applying a censored version of the Anderson-Darling test. Use the version of the test described in Section 9.6.1.4 for 20 percent censoring. If this test is not rejected, then the lower tolerance bounds should be computed using the methods described in 9.2.8 for 20 percent censoring. If the assumption of Weibullness is rejected here, then 50 percent censoring should be attempted, in the same manner as described for 20 percent censoring.

If the Weibull model is still rejected with 50 percent censoring, then a last resort conservative Weibull method should be attempted. This method decreases the initial Weibull threshold estimate while holding the shape and scale parameters constant, until the percentiles of the resulting model are sufficiently less than the sample percentiles. To avoid accepting an extremely inadequate fit, the decrease is limited to 0.5 ksi.

Section 9.6.1.6 describes the method for identifying a proper backoff (the decrease from the initial Weibull threshold estimate), denoted by $\tau_{backoff}$, for this method. If the appropriate backoff is less than or equal to 0.5 ksi, the lower tolerance bounds should be calculated by first computing bounds based on the complete sample as specified in Section 9.2.8, and then subtracting the $\tau_{backoff}$ value. If an appropriate backoff less than or equal to 0.5 ksi is not identified, then the nonparametric procedures described in 9.2.9, or the adjusted normal procedure described in Section 9.2.7, should be considered.

If the sequential Pearson analysis procedure is applied, the first step is to perform an Anderson-Darling goodness-of-fit test for Pearsonality as described in Section 9.6.1.7. If the assumption of normality is not rejected, the lower tolerance bounds may be computed using the methods described in Section 9.2.7. If the assumption of Pearsonality is rejected, then the Pearson backoff method should be attempted. This method decreases the estimate of the mean, while holding the standard deviation and skewness estimates constant, until the percentiles of the resulting model are sufficiently less than the sample percentiles. To avoid accepting an extremely inadequate fit, the decrease in the mean is limited to 0.5 ksi.

Section 9.6.1.8 describes the method for identifying a proper backoff, denoted by $\tau_{backoff}$, for the sequential Pearson method. If the appropriate backoff is less than or equal to 0.5 ksi, the lower tolerance bounds should be calculated by first computing bounds based on the complete sample as specified in Section 9.2.7, and then subtracting $\tau_{backoff}$. If an appropriate backoff less than or equal to 0.5 ksi is not identified, then the sequential Weibull procedures described in Section 9.2.8 or the nonparametric procedure described in Section 9.2.9 should be considered.

In those cases where sufficient data is available, one may choose to calculate the lower tolerance bounds by the nonparametric procedure. A T_{99} bound requires 299 data values and a T_{90} bound requires 29 data values.* The nonparametric procedure is described in Section 9.2.9. If the sample size is too small for the nonparametric method, the sequential Weibull procedure described in Section 9.2.8 or the sequential Pearson procedure described in Section 9.2.7, should be considered.

In those cases where sample sizes are insufficient to apply the nonparametric method, and the goodness-of-fit tests will not allow application of the sequential Weibull or sequential Pearson procedures, the lower tolerance bounds cannot be calculated.

9.2.7 DIRECT COMPUTATION BY THE SEQUENTIAL PEARSON PROCEDURE — This procedure should be used when a lower tolerance bound (T_{99}, T_{90}) is to be computed directly (not paired with another property for computational purposes) and the population may be interpreted to signify either the property measured (TUS, etc.) or some transformation of the measured value that is normally distributed. This procedure is applicable to F_{tu} and F_{ty}. It may also be used for F_{cy}, F_{su}, F_{bru}, and F_{bry} if sufficient quantity of data is available.

9.2.7.1 Data Requirements — Direct calculation of T_{99} and T_{90} values requires adequate data to determine (1) the form of distribution and (2) reliable estimates of the population mean and standard deviation. Prior experience with the material under consideration will help in determining sample size requirements. For a material, each population should be represented by a sample containing at least 100 observations. The sample shall include multiple lots, representing at least ten production heats, casts, or melts, from a majority of important producers. See Section 9.1.6.2 for definitions of lot, heat, cast, and melt. The sample should be distributed somewhat evenly over the size range applicable to the tolerance bound for the mechanical property. In order to avoid an undesirable biasing of the sample in favor of lots represented by more observations than other lots, the number of observations from each lot must be nearly equal.

Grouped data may be "ungrouped" and analyzed as described below, if grouped data are reported in intervals of 1 ksi or less. The uniform smoothing method for ungrouping grouped data should be used. For the uniform smoothing method, observations in an interval are spread uniformly over that interval. The ith observation in an interval is set equal to

$$a_i = L + \frac{i}{n+1}(U - L) \qquad i = 1,2,...,n$$

where

n = the number of observations in the interval
L = the lower end point of the interval
U = the upper end point of the interval.

9.2.7.2 Computational Procedure — To compute lower tolerance bounds for a population from the Pearson Type III (or gamma) family of distributions, it is necessary to have estimates of the mean, standard deviation, and skewness of the population. In what follows, these are denoted respectively by $\overline{X}$, S, and q. These estimates are also necessary for applying the Anderson-Darling (AD) test for Pearsonality (described in 9.6.1.2) and for the backoff part of the test (described in 9.6.1.7).

* However, according to current guidelines, a T_{90} value cannot be calculated for inclusion in MIL-HDBK-5 with fewer than 100 data values. See Section 9.2.9.1.

In what follows, $X_{(1)}, X_{(2)}, \ldots, X_{(n)}$ represent the sorted observations, from smallest to largest. Calculate the sample mean and sample standard deviation as usual:

$$\overline{X}=\frac{1}{n}\sum_{i=1}^{n} X_i$$

$$S=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(X_i-\overline{X}\right)^2}$$

The skewness is calculated as follows. First calculate the sample skewness:

$$Q=\sqrt{\frac{n}{(n-1)^3}}\bullet\frac{\sum_{i=1}^{n}(X_i-\overline{X})^3}{S^3}$$

If $Q = 0$, then let $q = 0$. If $Q \neq 0$, calculate the estimated threshold

$$T=\overline{X}-2\bullet S/Q$$

and use the following rules to define q:

a. If $Q > 0$ and $X_{(1)} < T$, then let $q=2\bullet S/(\overline{X}-0.99999X_{(1)})$.

b. If $Q < 0$ and $X_{(n)} > T$, then let $q=2\bullet S/(\overline{X}-1.00001X_{(n)})$.

c. Otherwise, $q = Q$.

If the data are not rejected by the Anderson-Darling test for Pearsonality (described in 9.6.1.2), then T_{99} and T_{90} should be calculated by the following formulae:

$$T_{99}=\overline{X}-k_{99}(q,n)\cdot S$$
$$T_{90}=\overline{X}-k_{90}(q,n)\cdot S$$

where

$$k_{99}(q,n)= z_{99}(q) + \exp\left[2.556-1.229q+0.987q^2-0.6542\cdot\ln(n)+0.0897q\cdot\ln(n)-0.1864q^2\cdot\ln(n)\right]$$

$$k_{90}(q,n)= z_{90}(q) + \exp\left[1.541-0.943q-0.6515q^2-0.6004\cdot\ln(n)+0.0684q\cdot\ln(n)+0.0864q^2\cdot\ln(n)\right]$$

$$z_{99}(q) = \frac{2}{q}\left[1 - \left(1 - \frac{q^2}{36} - 2.326348 \cdot \frac{q}{6}\right)^3\right] - 0.013133\ q^2 - 0.003231\ q^3 + 0.003139\ q^4 + 0.001007\ q^5$$

$$z_{90}(q) = \frac{2}{q}\left[1 - \left(1 - \frac{q^2}{36} - 1.281552 \cdot \frac{q}{6}\right)^3\right] + 0.003814\ q^2 - 0.002466\ q^3 - 0.000633\ q^4 + 0.000122\ q^5$$

The above formulas for $z_{99}(q)$ and $z_{90}(q)$ should be used for $q \neq 0$. If $q = 0$, then $z_{99}(q) = 2.326348$ and $z_{90}(q) = 1.281552$.

If the data are rejected by the Anderson-Darling test for Pearsonality, but accepted under the backoff option of the test (9.6.1.7) with a reduction in the mean of $\tau_{backoff}$, then the above formulas should be applied to compute then T_{99} and T_{90} with the following slight modification:

$$T_{99} = \overline{X} - k_{99}(q,n) \cdot S - \tau_{backoff}\,,$$
$$T_{90} = \overline{X} - k_{90}(q,n) \cdot S - \tau_{backoff}\,.$$

9.2.8 DIRECT COMPUTATION *BY THE SEQUENTIAL WEIBULL PROCEDURE* — This procedure should be used when a mechanical property value is to be computed directly (not paired with another property for computational purposes) and the population may be interpreted to signify either the property measured (TUS, etc.) or some transformation of the measured value that follows a three-parameter Weibull distribution. This procedure is applicable to F_{tu} and F_{ty}. It may also be used for F_{cy}, F_{su}, F_{bru}, and F_{bry} if a sufficient quantity of data is available.

9.2.8.1 Data Requirements — Direct calculation of the lower tolerance bounds (T_{99}, T_{90}) requires adequate data to determine (1) form of the distribution and (2) reliable estimates of population threshold, shape, and scale parameters. Prior experience with the material under consideration will help determine sample size requirements. For a material, each population should be represented by a sample containing at least 100 observations that are distributed (parametrically) according to a three-parameter Weibull distribution. The sample should include multiple lots, representing at least ten production heats, casts, or melts, from a majority of important producers. The sample should be distributed somewhat evenly over the size range applicable to the property. In order to avoid an undesirable biasing of the sample in favor of lots represented by more observations than other lots, the number of observations from each lot must be nearly equal.

Grouped data may be "ungrouped" and analyzed as described below, if grouped data are reported in intervals of 1 ksi or less. The uniform smoothing method for ungrouping grouped data should be used. For the uniform smoothing method, observations in an interval are spread uniformly over that interval. The ith observation in an interval is set equal to

$$a_i = L + \frac{i}{n+1}(U - L) \qquad i = 1,2,...,n$$

where

n	=	the number of observations in the interval
L	=	the lower end point of the interval
U	=	the upper end point of the interval.

9.2.8.2. *Computational Procedures* — In order to compute the lower tolerance bounds for a three-parameter Weibull population, it is necessary to have (1) an estimate of population threshold, (2) estimates of population shape and scale parameters, and (3) tables of one-sided tolerance limit factors for the three-parameter Weibull distribution. The method for estimating the population threshold based on complete or censored data (20 or 50 percent censoring) is presented in Section 9.6.5.1, and Section 9.6.5.2 contains the method for estimating population shape and scale parameters. Both of these procedures permit estimation with complete or censored data (20 or 50 percent censoring). A tabulation of tolerance limit factors by sample size, censoring level, and population proportion covered by the tolerance interval is presented in Table 9.6.4.8. For further information on these procedures and tabled values, see References 9.2.8(a) and 9.2.8(b).

Let $X_1,..,X_n$ denote sample observations in any order and let $X_{(1)},...,X_{(n)}$ denote sample observations ordered from smallest to largest. The first step in calculating T_{99} and T_{90} for a three-parameter Weibull population is to obtain an estimate of the population threshold. The population threshold is theoretically the minimum achievable value for the property being measured. However, the real population is being empirically modeled by some Weibull population with a threshold. Since this empirical model is not perfect, there may be a small percentage of observations in the population that fall below the model threshold. Separate threshold estimates, denoted by τ_{99} and τ_{90}, will be obtained for T_{99} and T_{90} using the methods described in Section 9.6.5.1.

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The second step in calculating mechanical properties for a three-parameter Weibull population is to obtain estimates of population shape and scale parameters for each property. Shape parameter estimates will be denoted by β_{99} and β_{90} and scale parameter estimates will be denoted by α_{99} and α_{90}. Estimation of shape and scale parameters is performed using a maximum likelihood procedure for the two-parameter Weibull distribution, after subtracting off the estimated threshold. (The two-parameter Weibull is equivalent to the three-parameter Weibull with threshold zero.)

Using the method outlined in Section 9.6.5.2, compute the maximum likelihood estimates of the shape and scale parameters for the censored or uncensored sample $\{X_{(i)} - \tau_{99} : i=1,...,r\}$, where r equals n for uncensored data and r represents the smallest integer greater than or equal to 4n/5 for 20 percent censoring and n/2 for 50 percent censoring. Denote these estimates by β_{99} and α_{99}, respectively. Using the same procedure, compute estimates β_{90} and α_{90} based on the sample $\{X_{(i)} - \tau_{90} : i=1,...,r\}$.

With population parameter estimates discussed above at hand, the computation of the lower tolerance bounds is carried out by use of the formulas:

$$T_{99} = \tau_{99} + Q_{99} \exp\left[-V_{99}/\left(\beta_{99}\sqrt{n}\right) \right],$$

$$T_{90} = \tau_{90} + Q_{90} \exp\left[-V_{90}/\left(\beta_{90}\sqrt{n}\right) \right],$$

where

Q_{99} = $\alpha_{99}\,(0.01005)^{1/\beta_{99}}$
Q_{90} = $\alpha_{90}\,(0.10536)^{1/\beta_{90}}$
V_{99} = the value in the V_{99} column of Table 9.6.4.8 corresponding to a sample of size n and the appropriate degree of censoring, and
V_{90} = the value in the V_{90} column of Table 9.6.4.8 corresponding to a sample of size n and the appropriate degree of censoring.

Note that the level of censoring used in estimating the threshold, shape, and scale parameters must be used in determining V_{99} and V_{90}. Also, because this censoring level is determined by the goodness-of-fit test (9.6.1.4), the same censoring level is used for both T_{99} and T_{90}.

If the property that follows a three-parameter Weibull distribution represents a transformation, the lower tolerance bounds (T_{99}, T_{90}) computed by the above formulas must be transformed back to the original units in which the mechanical property is conventionally reported. When the computed T_{99} or T_{90} value results in a fractional number, the mechanical property used in the room temperature tables is determined by rounding. Fractions greater than 0.75 usually are raised to the next larger integer while lesser decimal fractions are disregarded. However, the rounded T_{99} value is replaced in the mechanical property tables with the S value if the S value is lower. In that case the rounded T_{99} value is included in a footnote.

9.2.9 DIRECT COMPUTATION FOR AN UNKNOWN DISTRIBUTION — This procedure should be used when a mechanical-property value is to be computed directly (not paired with another property for computational purposes) and the form of the distribution of population is unknown (not normal or three-parameter Weibull). Distribution should not be considered unknown (1) if tests show it to be nearly normal or three-parameter Weibull, (2) if it can be transformed to a nearly normal or three-parameter Weibull distribution, or (3) if it can be separated into nearly normal or three-parameter Weibull subpopulations. This procedure is applicable to F_{tu} and F_{ty}. It may also be used for F_{cy}, F_{su}, F_{bru}, and F_{bry} if sufficient quantity of data is available.

9.2.9.1 *Data Requirements* — Data must be adequate to assure that the sample is representative of the population. Although censoring is highly undesirable, parametric techniques will

Prob. VII—Step 1. Pair SUS(LT) with TUS(LT).

Ratios of SUS(LT)/TUS(LT) are as follows:

SUS(LT)/TUS(LT)	Thickness, inch	SUS(LT)/TUS(LT)	Thickness, inch
0.700	0.020	0.640	0.090
0.680	0.020	0.650	0.090
0.660	0.020	0.660	0.090
0.660	0.030	0.630	0.100
0.670	0.030	0.650	0.100
0.680	0.030	0.670	0.100
0.650	0.040	0.640	0.150
0.670	0.040	0.630	0.150
0.690	0.040	0.620	0.150
0.650	0.060	0.610	0.180
0.660	0.060	0.630	0.180
0.670	0.060	0.650	0.180
0.640	0.070	0.600	0.240
0.660	0.070	0.610	0.240
0.680	0.070	0.620	0.240

Prob. VII—Step 2. Determine regression equation in the form [SUS(LT)TUS(LT)]′=r′=a + bx, where x = thickness, using least-squares techniques. (Note—in this example, the letter r, rather than y, is used to denote the dependent variable and the prime (′) is used to indicate that the ratio is determined by regression.) The following sums were obtained from analysis of the ratios plotted in Figure 9.2.12.

Number of ratios, n = 30

$\sum(x)$	= 2.94	$(\sum r)^2$	= 381.4209
$\sum(x^2)$	= 0.4260	$(\sum x)(\sum r)$	= 57.4182
$\sum(r)$	= 19.53	S_{xx}	= 0.1379
$\sum(r^2)$	= 12.7319	S_{xr}	= 0.0416
$\sum(xr)$	= 1.8723	S_{rr}	= 0.0179
$(\sum x)^2$	= 8.6436		

Referring to the equations presented in Section 9.6.3:

$$\text{Slope, } b = \frac{S_{xr}}{S_{xx}} = \frac{-0.0416}{0.1379} = -0.302$$

$$\text{Intercept, } a = \frac{\Sigma r - b\,(\Sigma x)}{n} = \frac{19.53 - (-0.302)(2.94)}{30} = 0.6806$$

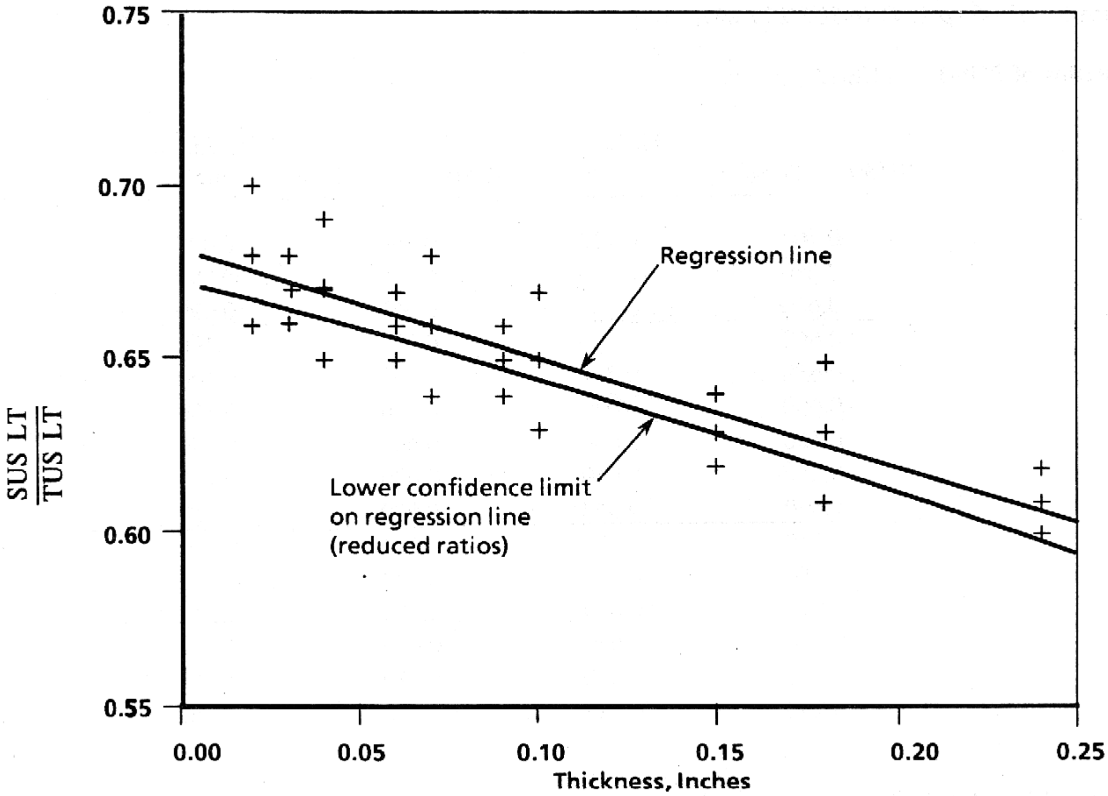

Figure 9.2.12. Ratios of input data for Problem VII.

Standard Error of Estimate,

$$s_{r'} = \sqrt{\frac{S_{rr} - b^2 S_{xx}}{(n - 2)}}$$

$$= \sqrt{\frac{0.0179 - (-0.302)^2(0.1379)}{(30 - 2)}}$$

$$= 0.014$$

The equation of the regression line is $r' = 0.6806 - 0.302x$.

The regression line is shown in Figure 9.2.12.

Prob. VII—Step 3. Perform an analysis of variance to check the significance and linearity of the regression.

Since there are 30 ratios, the analysis of variance approach rather than the method involving the computation of confidence limits on the slope term can be used to evaluate linearity.

The only information missing from Step 2 required for the analysis of variance is the values of T, or the summed values of r for each x. They are as follows:

$$R(\tau) = \sum_{i=89}^{262} L_i(\tau) \Big/ \sum_{i=1}^{262} L_i(\tau)$$

Solving the equation $R(\tau) = 0.665$ with initial interval (-279.9, 120.4869) gives $\tau_{50} = 119.58$. Solving the equation $G_{50}(\beta_{50}) = 0$ gives $\beta_{50} = 2.84$ which in turn gives $\alpha_{50} = 11.81$.

The values $Z_{(1)},...,Z_{(330)}$ are obtained using these estimates. The value of the Anderson-Darling test statistic is 1.392. Since the computed value of 1.392 is greater than the critical value of 0.749, the hypothesis that the observations follow a three-parameter Weibull distribution is rejected.

Prob. XII—Step 2. Compute F_{ty}(LT), 0.020 to 0.125, using procedures for an unknown distribution. This computation has been carried out in Problem V, Step 2.

9.2.13 MODULUS OF ELASTICITY AND POISSON'S RATIO — The following room-temperature elasticity values are presented in the room-temperature property tables as typical values:

Property	Units	Symbol	Recommended ASTM Test Procedures
Modulus of Elasticity			
In tension	1000 ksi	E	E 111
In compression	1000 ksi	E_c	E 111
In shear	1000 ksi	G	E 143
Poisson's Ratio	(Dimensionless)	μ	E 132

If the material is not isotropic, the applicable test direction must be specified. Deviations from isotropy must be suspected if the experimentally determined Poisson's ratio differs from the value computed by the formula

$$\mu = \frac{E}{2G} - 1 \qquad [9.2.13(a)]$$

where E is the average of E and E_c.

Given E, E_c, and G, μ may be computed by this equation. Likewise, given E, E_c, and μ, G may be computed from the equation:

$$G = \frac{E}{2(\mu + 1)} \qquad [9.2.13(b)]$$

In the event E_c is not available, E may be substituted for E in the above equations to provide an estimate of either μ or G.

9.2.14 PHYSICAL PROPERTIES — Density, specific heat, thermal conductivity, and mean coefficient of thermal expansion are physical properties normally included in MIL-HDBK-5. Physical properties are presented in the room-temperature property table if they are not presented in effect-of-temperature curves (see Section 9.3.1.4). The basis for physical properties is "typical". Table 9.2.14 displays units and symbols used in MIL-HDBK-5, and also recommended ASTM test procedures for measuring these properties. Since modifications of procedures are employed in measuring physical properties, methods used for values proposed for inclusion in MIL-HDBK-5 should be reported in the supporting data proposal. For specific heat and thermal conductivity values reported in the room temperature property table, the reference temperature of measurement is also shown [for example, for 2017 aluminum the specific heat is 0.23 (at 212EF)]. For tabulated values of mean thermal expansion, temperature range of the coefficient is shown [for example, 12.5 (70 to 212EF)]. The reference temperature of 70EF is established as standard for mean coefficient of thermal expansion curves.

Table 9.2.14. Units and Symbols Used to Present Physical Property Data and ASTM Test Procedures

Property	Unit	Symbol	Recommended ASTM Test Procedures
Density	lb/in.^{3}	ω	C 693
Specific heat	Btu/lb-EF	C	D 2766
Thermal conductivity	Btu(hr-ft^2-EF/ft)	K	C 714[a]
Mean coefficient of thermal expansion	10^{-6}(in./in./EF)	α	E 228

a ASTM C 714 is a test for thermal diffusivity from which thermal conductivity can be computed.

9.2.15 PRESENTATION OF ROOM-TEMPERATURE DESIGN VALUES — The proposal for the incorporation of design allowables into MIL-HDBK-5 shall contain supporting data and computations for all design properties. Depending on quantity and availability, data may be tabulated, plotted, or referenced (to readily available technical reports, specifications, etc.). Computations should indicate adequately the manner in which design values were computed and shall be presented in an orderly manner. Data sources shall be identified.

All minimum mechanical property data analyses must be performed in English units. Strength data recorded in metric units should be converted to English units, to the nearest 0.01 ksi, before data analyses are undertaken. If desired by the data supplier, metric equivalent tables and figures can be included as part of the working data submitted with a data proposal, but the tables and/or figures proposed for inclusion in MIL-HDBK-5 will contain only English units.

The table of room-temperature design values shall be presented in the format indicated in Figure 9.2.15(a) for conventional metallic materials. This format has been designed to accommodate most of these materials; however, some modifications may be required. For example, the format shown in Figure 9.2.15(b) shall be used for aluminum alloy sheet laminates which are generally anisotropic and have limited ductility. Design values for these hybrid materials are presented for several mechanical properties which differ from those shown for conventional metallic materials. Unused lines (for example, ST properties for sheet) are deleted. Guidance in the use of these formats may be obtained by examining tables throughout this document and by referral to the applicable procurement specification. The following instructions should be followed for the items located in Figure 9.2.15(a):

(1) Table number: If this is a revision of an existing table, use the same table number; otherwise, use a new table number in the proper sequence.

(2) Material designation: Use a numeric designation where available (for example, 7075 aluminum alloy). Avoid the use of trade names. Include products following the material designation, except products may be omitted from the title if there are many products covered by the table.

(3) Specification: Refer to a public specification (industry, Military, or Federal), followed by a type or class designation, if appropriate. Do not refer to proprietary specifications.

(4) Condition: Use a standard temper designation where applicable. Otherwise, use an easily recognized description, including pertinent details if these are not available in the reference specification. Examples: T651, TH1050, Aged (1400°F), Mill Annealed.

(5) Cross-sectional area: Use only when applicable.

(6) Location within casting: Applicable only to castings. Specify "Non-designated area," or "Designated area," as applicable.

(7) Design values shall be presented only for the thicknesses covered in the material specification.

(8) Basis: For each product and size, use two columns covering A- and B-basis properties or one column covering S-basis properties. A-values that are higher than the corresponding S-values are presented only in footnotes to the table. In such instances, A-values are replaced by S-values in the body of the table. When A-values are presented for some properties and S-values are presented for other properties for the same product, values shall be shown in a column labeled A-basis, and individual S-values shall be identified by appropriate footnotes. Elongation, total strain at failure, and reduction of area values are presented on an S-basis only. When other properties are presented on an A- and B-basis, add "(S-basis)" after "*e*, percent," or "ε_t percent" and "*RA*, percent." For aluminum alloy die forgings, F_{tu}, F_{ty}, and *e* shall be shown on an S-basis only for transverse, T, grain direction. To explain, add the following footnote to these values, "Specification value. T tensile properties are presented on an S-basis only." Design values for low alloy, quenched and tempered steels shall be presented on an S-basis only.

(9) Grain direction: Show design values for grain directions "L, LT, and ST" or for grain directions "L and T" for the properties F_{tu}, F_{ty}, F_{cy}, *e*, and *RA*. For anisotropic materials, present design values for grain directions "L, 45°, and LT" for F_{tu}, F_{ty}, and F_{cy}. For aluminum alloy sheet laminates, show design values for L and LT grain directions of aluminum alloy sheet for all mechanical properties. Grain directions are not applicable to castings.

The T grain direction should be footnoted with the definition used in the specification identified at the top of the mechanical property table. For example, the T grain direction for aluminum die forgings covered in MIL, Federal and some AMS specifications will read as follows: "For die forgings, T indicates any grain direction not within ±15 degrees of being parallel to the forging flow lines." For updated AMS specifications with the preferred narrower definition of the T grain direction, the footnote should read as follows: "For die forgings, T indicates a grain direction within ±15 degrees of being perpendicular to the forging flow lines." Specimens to test the transverse properties should be located as close to the short transverse direction as possible.

Transverse F_{cy} values for aluminum die forgings shall be shown as F_{cy}(T). If the values are based upon short transverse or long transverse test data, add this information to the above footnote.

(10) Missing values: For table entries that are missing or not applicable, show a series of three dots aligned with the numbers in that column.

(11) Bearing values: Add footnote "Bearing values are dry pin values per Section 1.4.7.1" when bearing allowables are based on data from clean pin tests. Supporting information supplied with the proposal should describe the bearing test cleaning procedures used in testing.

(12) Physical properties: Include a section for physical properties even if properties are not available. If physical property data are presented in an effect-of-temperature curve, use table entry, "See Figure X.X.X.0" to refer to the illustration.

(13) Footnotes: Use footnotes to indicate anything unusual or restrictive concerning the property description, properties, or individual values; to present supplementary values; or to reference other tables or sections of text. When A-values have been replaced by S-values, the following wording is suggested: "S-basis. The rounded T_{99} values are as follows: (list values)."

In addition, the proposal shall contain supporting data and computations for all design properties. Depending on quantity and availability, data may be tabulated, plotted (by cumulative-probability curves or histograms), or referenced (to readily available technical reports, specifications, etc.). Computations should indicate adequately the manner in which design values were computed and shall be presented in an orderly manner. Data sources shall be identified.

Using the data corresponding to all strain ratios other than R_ϵ = -1, fit the regression equation

$$S_m = \alpha_2 + \beta_2 \, (\Delta\epsilon/2)$$

using weighed least squares to give higher weight to the observations which exhibit partial mean stress relaxation. If there is no way to directly calculate S_m from the data reported in the data set, an S_m value for use in fitting the above regression equation may be calculated by solving Equation 9.3.4.16(c) for S_a and subtracting this value from the reported S_{max} value. The weighting function

$$w = \left(|S_m| / S^* \right) \left(1 - S_m / S^* \right)^2$$

where

$$S^* = \left[\left(1 + R_\epsilon \right) / \left(1 - R_\epsilon \right) \right] E \, \left(\Delta\epsilon/2 \right)$$

appears to work well in general. Assuming that the mean stress relaxation pattern is independent of strain ratio and provided that the estimate of the parameter β_2 is less than zero, a mean value for S_m can be determined as a function of strain range and strain ratio according to the formula

$$S_m = \begin{cases} \beta_3 (\Delta\epsilon/2) & (\Delta\epsilon/2) \le \alpha_2 / (\beta_3 - \beta_2) \\ \alpha_2 + \beta_2 (\Delta\epsilon/2) & \alpha_2/(\beta_3 - \beta_2) \le \Delta\epsilon/2 \le -\alpha_2/\beta_2 \\ 0 & -\alpha_2/\beta_2 \le (\Delta\epsilon/2) \end{cases}$$

where

$$\beta_3 = \left[(1 + R_\epsilon) / (1 - R_\epsilon) \right] \overline{E} \quad .$$

If the estimate of parameter β_2 is greater than or equal to zero, the data set should be examined further before proceeding with the analysis.

Mean curves determined according to the above procedures exhibit the following characteristics:

(1) At large strain ranges, enough plastic strain is available to relax at the mean stress to zero, regardless of the strain ratio. Therefore, all strain ratios result in equivalent predicted fatigue lives.

(2) At strain ranges corresponding to mean stresses represented by the relaxation regression line, strain ratios other than R_ϵ = -1 (zero mean stress) result in equivalent predicted fatigue lives.

(3) At low strain ranges, the individual strain ratios assume their elastic mean stress response and diverge from each other.

The above procedure is used for plotting the strain-life curves in MIL-HDBK-5 when multiple strain ratios are involved.* The curves generally represent the mean data trends closely.

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* In the general case, data generated at different strain ratios will not necessarily follow the same mean stress relaxation pattern. If different patterns for each strain ratio are evident in a particular case, it is suggested that a family of mean stress relaxation curves be constructed.

In addition to the strain-life plot, stress-strain curves and mean stress relaxation curves should be presented as shown in Figure 9.3.4.16(a). A tabulation of test and material conditions should also be included as shown in Figure 9.3.4.16(b). This information should include:

(1) Material
(2) Product Form, Grain Direction, Thickness, Processing History, Fabrication Sequence
(3) Test Parameters
- Strain Rate and/or Frequency
- Wave Form
- Temperature
- Environment

(4) Average Tensile Properties
(5) Stress-Strain Equation
- Monotonic (if available and appropriate) - Cyclic

(6) Specimen Details
- Specimen Type
- Specimen Dimensions
- Fabrication Sequence

(7) Surface Condition/Surface Residual Stresses/Finish
- Finish
- Residual Stress Data

Correlative Information for Figure 9.3.4.16(a)

Product Form: Die forging, 2-inch thick

Thermal Mechanical Processing History:
Annealed at 1800EF, water quench

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp.,EF
155-160	135-140	29,000	250

Stress-Strain Equations:
Monotonic
Proportional Limit = 111 ksi
$\sigma = 289\ (\varepsilon_p)^{0.138}$
Cyclic (Companion Specimens)
Proportional Limit = 92 ksi
$(\Delta\varepsilon/2) = 156\ (\Delta\varepsilon_p/2)^{0.046}$
Mean Stress Relaxation
$\sigma_m = 114.0\text{-}24562(\Delta\varepsilon/2)$

Specimen Details:
Uniform gage test section
0.250-inch diameter
Polished with increasingly finer grits of emery paper to surface roughness of 10 RMS with polishing marks longitudinal.

Reference: 3.4.5.6.8(a)

Test Parameters:
Strain Rate/Frequency - 180 cpm
Wave Form - Sinusoidal
Temperature - 250EF
Atmosphere - Air

No. of Heats/Lots: 2

Equivalent Strain Equation:
$\text{Log } N_f = -6.56\text{-}4.20 \log (\varepsilon_{eq}\text{-}0.0022)$
$\varepsilon_{eq} = (\Delta\varepsilon)^{0.46}\ (S_{max}/E)^{0.54}$
Std. Error of Estimate, Log (Life) =0.123
Standard Deviation, Log (Life) = 0.465
$R^2 = 93\%$

Sample Size = 33

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

Figure 9.3.4.16(b). Example of correlative information and analysis results for a strain control fatigue data presentation.

Correlative Information for Figure 9.3.4.17(c)

Product Form: Bar, 1-inch thick

Thermal Mechanical Processing History:
Not available

Properties:

TUS, ksi	TYS, ksi	E, ksi	Temp.,EF
175-180	150-155	27,500	70

Stress-Strain Equations:

Monotonic

Proportional Limit = 150 ksi

$\sigma = 280\ (\varepsilon_p)^{0.12}$

Cyclic (Companion Specimens)

Proportional Limit = 105 ksi (est.)

$(\Delta\sigma/2) = 196\ (\Delta\varepsilon_p/2)^{0.076}$

Mean Stress Relaxation

$\sigma_m = 125.4\text{-}25666(\Delta\varepsilon/2)$

Specimen Details:
Uniform gage test section
0.200-inch diameter

Reference: 3.4.5.6.8(a)

Test Parameters:
Strain Rate/Frequency - 180 cpm
Wave Form - Sinusoidal
Temperature - 700EF

No. of Heats/Lots: 4

Equivalent Strain Equation:

Log N = -5.07-3.47 log (ε_{eq}-0.00198)

$\varepsilon_{eq} = (\Delta\varepsilon)^{0.61}\ (S_{max}/E)^{0.39}$

Std. Error of Estimate, Log (Life) = 0.111

Standard Deviation, Log (Life) = 0.555

R^2 = 96%

Sample Size = 29

[Caution: The equivalent strain model may provide unrealistic life predictions for strain ratios and ranges beyond those represented above.]

Figure 9.3.4.17(c). ε/N curve and correlative information for iron alloy at 700EF — Continued.

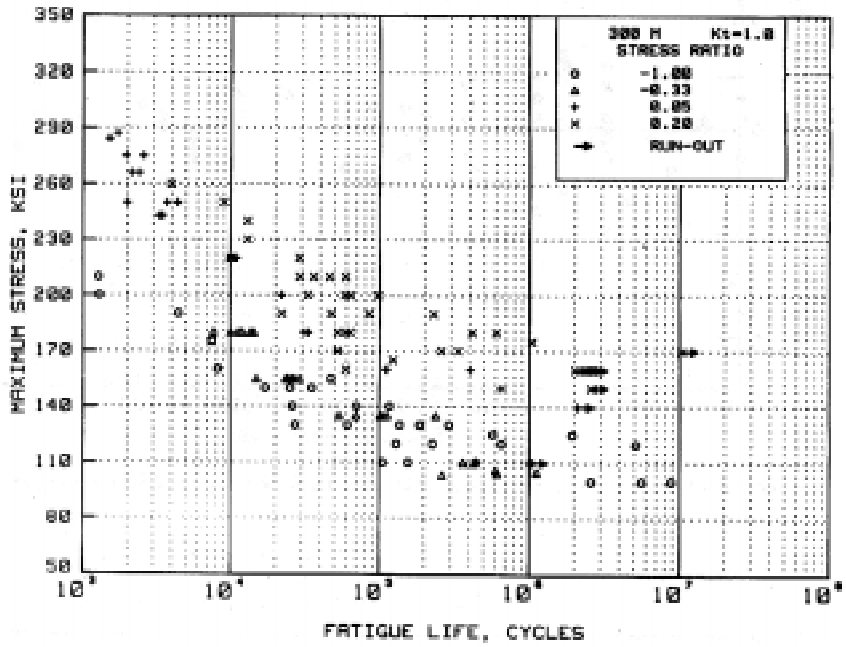

Figure 9.3.4.17(d). S/N plot of unnotched 300M die forging fatigue data, transverse orientation.

The fatigue-limit parameter (A_4) of zero seems somewhat inconsistent with the data shown in Figure 9.3.4.17(d). A visual examination of the S/N plot reveals a tendency for the data to asymptotically approach some limiting value. The zero fatigue limit term suggests that some problem may exist within the data collection. A plot of the residuals for the fatigue model using these parameters is shown in Figure 9.3.4.17(e).

The parameters obtained after the model is adjusted for nonconstant variance are:

$$A_1 = 23.4$$
$$A_2 = -8.38$$
$$A_3 = 0.40$$
$$A_4 = 13.5.$$

Note that a fatigue limit term of 13 ksi has now been estimated. However, a check on the significance of the A_4 term revealed that it was clearly insignificant. All of the runouts in the data collection were above this equivalent stress level and, therefore, all runouts were used in the regression procedure. A plot of the residuals after the fatigue life model has been adjusted is shown in Figure 9.3.4.17(f). Note the relative shift in the magnitude of the residuals at the higher and lower S_{eq} values compared to Figure 9.3.4.17(e).

Treatment of Outliers (See Section 9.3.4.11) — None of the observations were identified as outliers. The critical studentized residual at the 5 percent significance level for this data set of 114 observations is 3.63. The largest standardized residual was 3.23, resulting from a runout observation.

The modified data collection is now reanalyzed. For the sake of brevity, the details of the analysis procedure for Sections 9.3.4.4 (Data Requirements) through 9.3.4.11 (Treatment of Runouts) will be omitted. It is interesting to note, however, that the fatigue limit term (A_4) resulting from the least squares regression with the R = -0.33 data excluded is 94.2 ksi. This result more realistically represents the longer life fatigue trends compared to the previous (insignificant) estimate of 13.5 ksi. With the suspect data removed, the equivalent stress model is determined to be acceptable at the 5 percent level. The Durbin-Watson D statistic also is increased to 2.18 indicating that the model now provides an adequate fit to the data.

Dataset Combination (See Section 9.3.4.13) — With the exclusion of the source containing the R = -0.33 data, the remaining data set combination is determined acceptable at the 5 percent level.

Treatment of Runouts (See Section 9.3.4.14) — The data collection includes seven runout observations. The maximum likelihood procedure has the effect of essentially shifting these runouts to the fatigue lives at which they most likely would have failed. The resulting fatigue life model parameters should reflect the slight increase in estimated fatigue life over the least squares parameters, particularly in the long life region. In general, the maximum likelihood regression will result in a higher intercept term (A_1) and a steeper (more negative) slope (A_2). The A_3 and A_4 terms are taken as constants to reduce the problem to a linear analysis.

The parameters resulting from the least squares regression are:

$$\begin{aligned} A_1 &= 14.54 \\ A_2 &= -5.04 \\ A_3 &= 0.385 \\ A_4 &= 94.2. \end{aligned}$$

The maximum likelihood parameters conform to the expected trends for A_1 and A_2:

$$\begin{aligned} A_1 &= 14.79 \\ A_2 &= -5.16 \\ A_3 &= 0.385 \\ A_4 &= 94.2. \end{aligned}$$

Note the increase in A_1 and the decrease (more negative slope) in A_2.

Presentation of Fatigue Analysis Results (See Section 9.3.4.16)—The stress-life curve and correlative information shown in Figure 9.3.4.17(h) is typical of a MIL-HDBK-5 load-control fatigue data proposal.

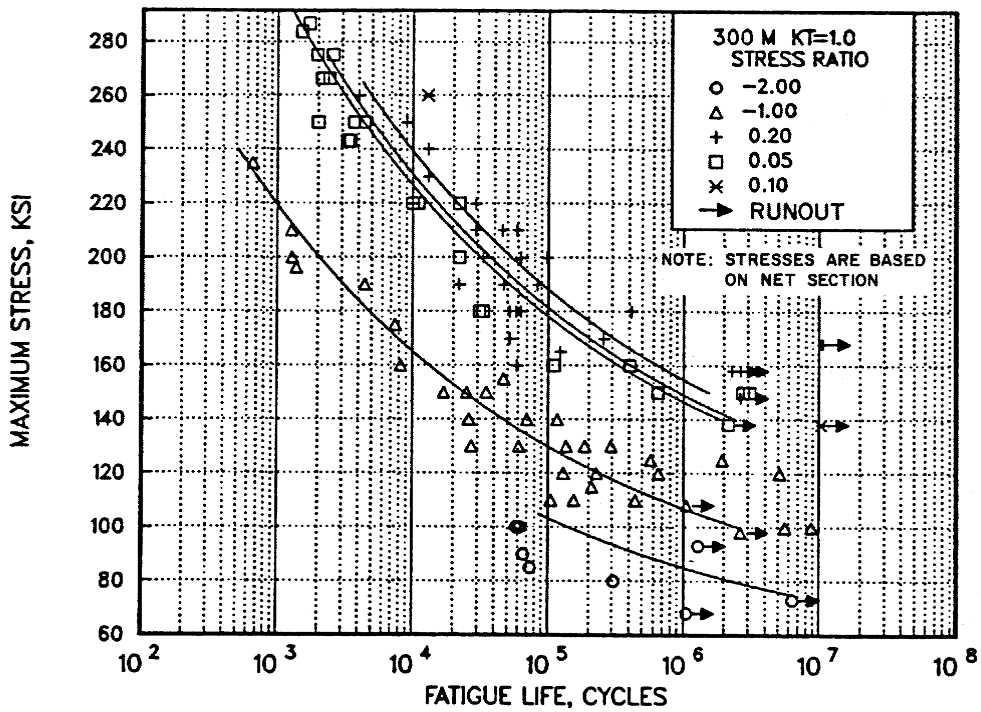

Figure X.X.X.X.X. Best-fit S/N curves for unnotched 300M alloy forging, F_{tu} = 280 ksi, longitudinal and transverse directions.

Correlative Information for Figure X.X.X.X.X

Product Forms: Die forging, 10 x 20 inches CEVM
Die forging, 6-1/2 x 20 inches CEVM
RCS billet, 6 inches CEVM
Forged Bar, 1-1/4 x 8 inches CEVM

Properties:

TUS, ksi	TYS, ksi	Temp., EF
274-294	227-247	RT

Specimen Details: Unnotched
0.200 - 0.250-inch diameter

Surface Condition: Heat treat and finish grind to a surface finish of RMS 63 or better with light grinding parallel to specimen length, stress relieve

References: 2.3.1.4.8(a), (c), (d), (e)

Test Parameters:
Loading - Axial
Frequency - 1800 to 2000 cpm
Temperature - RT
Atmosphere - Air

No. of Heat/Lots: 6

Equivalent Stress Equation:
Log N_f = 14.8-5.38 log (S_{eq}-63.8)
$S_{eq} = S_a + 0.48\, S_m$
Std. Error of Estimate, Log (Life) = 55.7 (1/S_{eq})
Standard Deviation, Log (Life) = 1.037
R^2 = 82.0

Sample Size = 104

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above.]

Figure 9.3.4.17(h). Example S/N curve and correlative information.

9.4.1.3 *Data Generation* — Development of mechanically fastened joint allowables from test data usually is accomplished with the aid of graphic analysis. Coordinates of the graph are P/D^2 and t/D, where P is subscripted P_u for ultimate load and P_y for yield load. The analysis assumes that design of a line of fasteners (a given configuration, material, and range of diameters) is proportional so that, when data from tests are plotted with the above coordinates, all data for all diameters can be represented by a single design curve. A schematic diagram of such a design curve for ultimate load is shown in Figure 9.4.1.3.

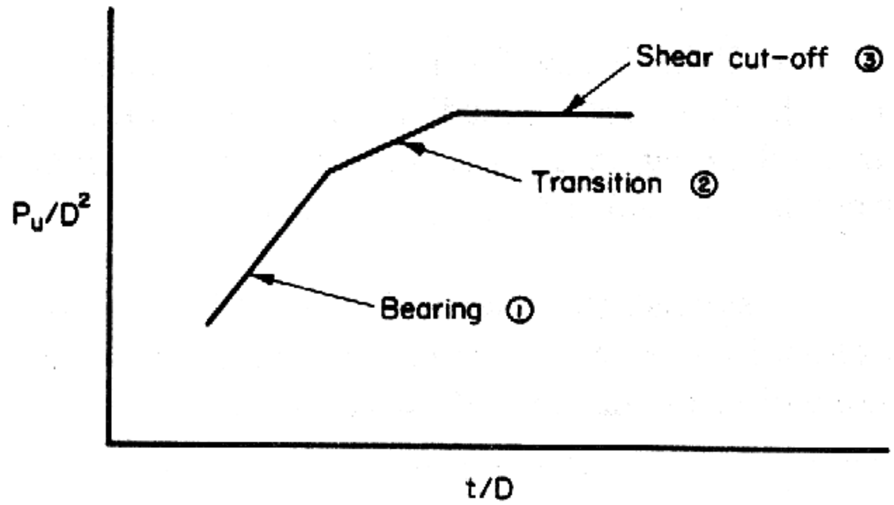

Figure 9.4.1.3. Schematic diagram of P_u/D^2 versus t/D.

Note there are three regions to the curve as follows:

Region 1, in which the joint failure mode is by sheet bearing.

Region 2, which is a transition failure zone in which failure may be by other means, such as head pulling through sheet, tension or shear of the fastener head, etc.

Region 3, in which the joint failure mode is by fastener shear.

The design curve shall be constructed so that all data fall to the left and above.

Data required for determining mechanically fastened joint allowables are based on results of single-shear lap-joint tests over the three regions described above, and fastener shear tests (usually, double shear tests in hardened steel test plates or fixtures). For driven rivets and blind fasteners, the single-shear lap-joint test in hardened steel test plates may be used to obtain shear strength or cutoff (Region 3). It is preferred, however, that shear strength be obtained from double shear tests of the fastener. Fastener system tensile strength data are required for all fasteners except solid and blind rivets (see Section 9.4.1.4.2). Sheet tensile test data also are necessary (see Section 9.4.1.4.5).

9.4.1.3.1 *Testing Equipment and Procedures* — Room-temperature testing equipment and procedures should comply with the provisions of NASM 1312, Tests 4, 13, and 20 [References 9.4.1.3.1(a) through (c) for both single- and double-shear tests.

9.4.1.3.2 *Specimen Design Configuration* — Specimen design should be as provided in NASM 1312, Test 4, Figure 1, Reference 9.4.1.3.1(a).

9.4.1.3.3 *Yield Load Definition* — Joint yield loads for all fasteners are defined as loads which result in 0.04D permanent set in the joint when the fastener is tested in nominal hole size as defined in Table 9.4.1.2. For some fastening systems, tests in larger hole sizes, although within manufacturer's recommended hole size limits, may result in joint permanent sets greater than 0.04D* at yield load.

9.4.1.3.4 *Yield Load Determination* — The preferred method of determining yield load is by the secondary modulus method.** To obtain secondary modulus line, during the test the joint is unloaded from a load close to, and preferably above, estimated yield load to a load value in the range of about 10 to 20 percent of estimated yield load. The joint then is reloaded and secondary modulus is the slope of this second loading line. This procedure is described in Reference 9.4.1.3.1(a) and is illustrated in Figures 9.4.1.3.4(a) through (e).

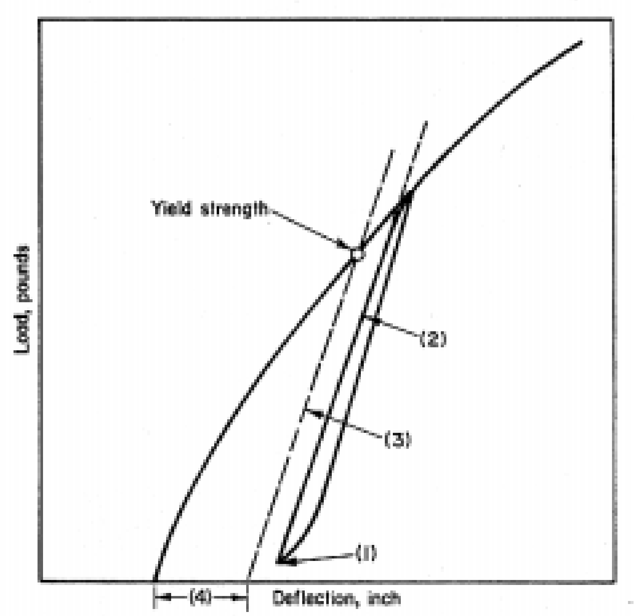

Figure 9.4.1.3.4(a). Illustration of secondary-modulus method of yield strength determination.

(1) Reduce load to 10-20 percent of yield load.
(2) Secondary-modulus line. The straight part of the loading side of the secondary-modulus loop indicating elastic behavior.
(3) Offset line. A line parallel to the secondary-modulus line.
(4) Offset. Equal to permanent set value specified in Section 9.4.1.3.3.

If curves similar to Curves A and B in Figure 9.4.1.3.4(b) are obtained early in the test program, strain hardening will be presumed. In that case, unloading should be delayed in subsequent tests until after anticipated yield load. Curves showing strain hardening may be extrapolated a reasonable amount to determine yield load by the secondary modulus method as shown.

The initial loading line is used to establish the intersection with the abscissa from which to measure yield offset. At times, minor irregularities occur on initial loading which necessitates redrawing of the lower part of the curve as a continuation of the normal curve, as shown in Curves C and D of Figure 9.4.1.3.4(c).

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* Or previous yield load criteria used prior to 1973. Applicable yield criteria are noted in footnote for design allowable table.

** The primary modulus line has been used in the past, on occasion. It is the slope of the initial loading line and frequently is observed to have greater variability than the secondary modulus line.

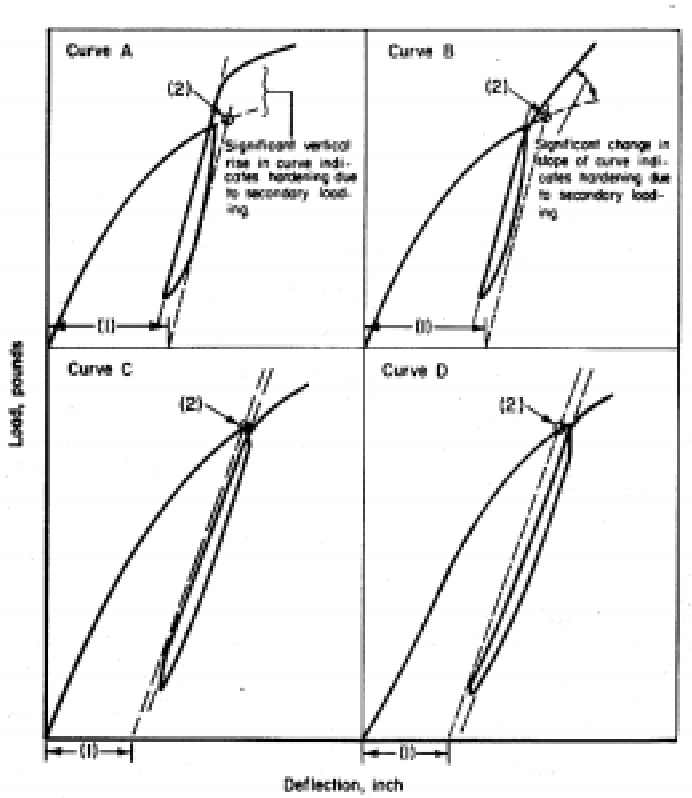


Figure 9.4.1.3.4(b). Sample secondary modulus load-deflection curves.

(1) Offset per 9.4.1.3.3.
(2) Joint yield strength.

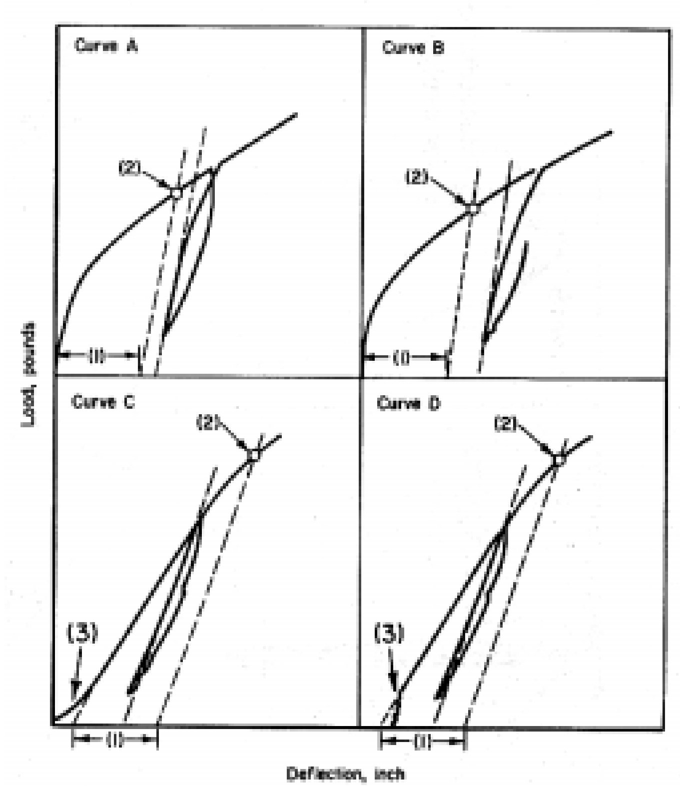


Figure 9.4.1.3.4(c). Sample secondary-modulus load-deflection curves.

(1) Offset per 9.4.1.3.3.
(2) Joint yield strength.
(3) Disregarded irregularities, per 9.4.1.3.

Unusually shaped curves are sometimes obtained. Typical of these are the illustrations in Figure 9.4.1.3.4(d). Data which are typified by Curves A or B are unacceptable for analysis. When the secondary modulus has a straight-line portion of recognizable length, do as shown in Curve C. When the secondary curve has two straight parts, but is more in question (as in Curve D), and there are satisfactory curves available from similar group test specimens, use the slope which approximates other curves. Otherwise, the more conservative (steepest) shall be used. An acceptable alternate is to draw a straight line between end points of the off-loading-reloading loop and consider this as the secondary modulus line, as shown in Figure 9.4.1.3.4(e). The primary modulus method may be used as a last resort, if there is no straight-line portion or usable loop in the secondary modulus curve.

9.4.1.4 ***Quantity and Distribution of Test Data*** — This section delineates required data to develop the design curve shown schematically in Figure 9.4.1.3. There are three facets to consider, which are described in following subsections: (1) shear strength of the fastener, Region 3; (2) shear critical strength, bearing and transition regions, Regions 1 and 2; and (3) tensile properties of sheet and plate material used in the joint.

A fourth subsection is concerned with the case when data are required for certification purposes (not for use in MIL-HDBK-5) for a specific thickness and fastener diameter.

9.4.1.4.1 *Shear Strength of Fastener* — Although many fasteners for which joint allowables are given in MIL-HDBK-5 are covered by MIL and NAS specifications (which provide for minimum shear strength values), many proprietary fasteners are listed wherein minimum shear strength values are established by the manufacturer. In either case, sufficient testing is necessary to establish minimum values. The intent of this subsection is to provide minimum test requirements to document shear strength of fasteners appearing in MIL-HDBK-5, regardless of specification source.

Shear strengths shall be determined from shear-critical single-shear test results or double-shear test results. Double-shear test results performed in accordance with NASM 1312, Test 13, are preferred over single-shear results, except for blind fasteners and driven rivets. For these latter fasteners, shear-critical tests shall be conducted with all components in the installed condition in hardened steel test plates. NASM 1312, Test 20, is the preferred test method. Furthermore, when fasteners of a given configuration and material are identical in every respect except for head size and shape, fastener shear test data are necessary only on one head style.

The minimum quantity of shear tests required for each fastener diameter for which allowables are to be established is 15. Fasteners for each diameter shall be selected from at least three production lots that represent at least two heats of the fastener component materials.

Fasteners developed from materials not previously used for fastener applications will require additional testing in order to determine statistically reliable minimum shear strengths. Test values should be developed in accordance with the test methods noted above using hole sizes specified in those methods or Table 9.4.1.2, as appropriate. Test values shall represent a minimum of 10 tests from each of 10 production lots made of at least 3 heats of material (100 tests). Fasteners tested should be evenly distributed over the diameter range under consideration with grip ranging from 2 to 3 diameters for solid and blind rivets and any appropriate length for solid shank fasteners. Shear strength (F_{su}) should be computed based on hole size for solid and blind rivets and measured shank diameter for non-hole filling blind fasteners and pins. Data shall be checked for normality and if distribution is found to be normal:

value for which the countersink still is contained within the top sheet. For these cases, footnote (f) will be used, as indicated in Item (17).

(17) Add all applicable footnotes from the list of standard notes shown below. All footnotes shall be designated by lower case letters.

(a) "Yield value is less than two-thirds of the indicated ultimate strength value." (Place footnote indicator next to applicable ultimate strength value.)

(b) "These allowables apply to double-dimpled sheets and to the upper sheet dimpled into a machine-countersunk sheet. The thickness of the machine-countersunk sheet must be at least one tabulated gage thicker than the upper dimpled sheet." (Place footnote indicator next to the words "Ultimate Strength, lbs" at the top of the table.)

(c) "Data supplied by ABC Corporation." When applicable add: "Confirmatory data provided by XYZ Company." (Place footnote indicator next to part number.)

(d) "Shear strength based on areas computed from nominal hole diameters or nominal shank diameters, as applicable (indicate Table 8.1.2(a), or list hole diameters), and F_{su} = (indicate shear strength)." Indicate the source of the shear strength (MIL or NAS specifications or data analysis). The footnote indicator is placed next to the words "Fastener shear strength" indicated by Item 13 above. The shear strength shall not be greater than the strength required in the controlling specification or standard.

(e) "Allowables based on nominal hole diameters of (list hole diameters)." This footnote is used when shear strength is controlled by MIL or NAS specifications, and Table 8.1.2(a) hole diameters are not used.

(f) "Values above line are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires specific approval of the procuring agency."

(g) "Permanent set at yield load: 4% of nominal diameter (see Section 9.4.1.3.3)."

(h) "Fasteners installed in clearance (or interference) holes." Indicate actual range of fastener-hole fits (interference-clearance) from test program.

(i) "System maximum tensile strength as tested in steel fixture." This footnote is used when table contains fastener tensile strength values. (Place footnote indicator next to the words "Fastener tensile strength, lbs".)

(18) When applicable, add line below yield strength section to present "Fastener tensile strength, lbs". List the appropriate value for each fastener diameter.

(19) For flush head fasteners, add line below yield strength section to present "Head height (ref.), in." List appropriate value for each fastener diameter.

9.4.1.7 *Required Information* —

9.4.1.7.1 *Introduction to New Fastener* — When introducing a new fastener for possible inclusion in MIL-HDBK-5, sponsor shall submit a written request (on company letterhead) to Chairman, MIL-HDBK-5 Coordination Group, providing the following information:

(1) A description of the fastener such as: (a) type of fastener (driven rivet, blind fastener, swaged collar, etc.), (b) fastener material (alloy and temper), (c) unique or new features, (d) nominal sizes and actual diameters, and (e) part drawings and functional description.

(2) Reason for fastener usage or intended usage such as: (a) higher strength, (b) higher or lower temperature capability, (c) improved fatigue performance, and (d) lower installed cost.

(3) Development and use status. (It is not required that the fastener system actually be in use on production airframe structure, but there should be a high level of interest and an intent to use the fastener.) (a) What are current or planned airframe applications? (b) How long has the fastener been produced on a production (nonexperimental) basis? Include preliminary lap joint test data that demonstrates that sufficient diameters and grips are available to conduct a design allowable test program (i.e., data for at least one test for each diameter/grip combination contained in the proposed test plan).

(4) Specification status. Under what type of specification is the fastener covered (MS, NAS, airframe or fastener company standard)?

(5) In what sheet or plate material will the fastener be installed? (The proposed allowables should be for the same or similar sheet or plate material that the sponsor is using or plans to use.)

(6) Shank deformation. Does shank deform during installation? Verification is desirable. (a) If a blind fastener, is it hole filling or nonhole filling? Verification of hole fill is desirable. (b) If a solid shank fastener, are design values to be presented for clearance or interference holes?

(7) Has the sponsor conducted any testing on the fastener system (especially joint allowables) and will the sponsor provide data to the MIL-HDBK-5 Coordination Group?

(8) Has the sponsor reviewed (or will the sponsor review) test program plan, actual testing, analysis of data, and specifications?

9.4.1.7.2 *Final Report* — A report will be submitted to MIL-HDBK-5 Coordination Group summarizing the test program, results, analysis, and suggested table of joint allowables for MIL-HDBK-5. The following information will be provided in the report:

(1) A description of sheet and plate material with heat-treatment details and mechanical property test data for each sheet thickness used in the program in accordance with the requirements of Section 9.4.1.4.5.

(2) A description of fastener, including drawings and specifications. If the fastener is not covered by a government or industry specification, a copy of an appropriate draft specification will be attached to the report.

(3) A statement of compliance with NASM 1312, including a detailed statement of any differences from this standard.

9.6 STATISTICAL PROCEDURES AND TABLES

This section includes a number of statistical aids for use in preparation of data for MIL-HDBK-5. These aids are intended to supplement, not to replace, the basic procedure described elsewhere in these Guidelines.

Many different statistical techniques may be useful in analysis of mechanical-property data. This section presents brief descriptions of procedures that will be used most frequently in this application. More detailed descriptions of these and other statistical techniques and tables in their various forms can be found in a number of workbooks and texts; Reference 9.6 is a particularly useful one.

When procedures other than those described below are employed in preparation of data proposals, they should be described adequately in the proposal.

9.6.1 GOODNESS-OF-FIT TESTS

9.6.1.1 *Introduction* — The computational procedure selected to establish design-allowable values by statistical techniques is dependent upon distribution of strength measurements in the available sample. Both three-parameter Weibull and Pearson Type III distributions may be used. Some procedures in the Handbook require that residuals from a model be normally distributed. As noted previously, references to normal, Weibull, or Pearson Type III distributions shall be interpreted as applying either to original measurements or to an appropriate transformation of them. This section contains a discussion and illustration of methods used to establish whether or not a population follows a normal, Weibull, or Pearson Type III distribution.

Several goodness-of-fit test procedures are described below. The purpose of each is to indicate whether an initial distribution assumption should be rejected. The methods presented are based on the "AndersonDarling" goodness-of-fit family of tests. These tests are objective and indicate (at 5 percent risk of error) whether the sample is drawn from the tested distribution. Unfortunately, these tests may reject the assumed distribution even though the distribution may provide a reasonable approximation within the lower tail. For this reason, the sequential Weibull procedure permits upper tail censoring when found to be appropriate, and the goodness-of-fit test described below allows for this. Nonetheless, some subjective reasoning should be employed after using a goodness-of-fit test.

After a goodness-of-fit test has been performed (especially if the distributional assumption has been rejected), it is generally required that a cumulative probability plot of data be provided to graphically illustrate the degree to which the assumed distribution fits the data. Methods for development of normal probability plots (Section 9.6.1.3), Weibull probability plots (Section 9.6.1.5), and Pearson probability plots (Section 9.6.1.9) are presented.

In what follows, sample size is denoted by n, sample observations by $X_1, ..., X_n$, and sample observations ordered from least to greatest by $X_{(1)}, ..., X_{(n)}$. Data must be ungrouped.

9.6.1.2 *"Anderson-Darling" Test for Normality* — The "Anderson-Darling" test for normality is used to determine whether the curve which fits a given set of data can be approximated by a normal curve. The essence of the test is a numerical comparison of the cumulative distribution function for observed data with that for the fitted normal curve over the entire range of the property being measured. Let

$$Z_{(i)} = \left(X_{(i)} - \overline{X}\right)/s \quad i = 1,...,n$$

where $X_{(i)}$ is the i[th] smallest sample observation, $\overline{X}$ is the sample average, and s is the sample standard deviation. Equations for computing sample statistics are presented in Section 9.2.2.3.

The "Anderson-Darling" test statistic is

$$AD = \left[\sum_{i=1}^{n} \frac{1-2i}{n}\left[\ln\left(F_o\left(Z_{(i)}\right)\right) + \ln\left(1 - F_o\left(Z_{(n+1-i)}\right)\right)\right]\right] - n$$

where F_o is the standard normal distribution function*. If

$$AD > 0.752/\left(1 + 0.75/n + 2.25/n^2\right)$$

one may conclude (at 5 percent risk of error) that the population from which the sample was drawn is not normally distributed. Otherwise, the hypothesis that the population is normally distributed is not rejected. For further information on this test procedure, see References 9.6.1.2(a) and (b).

The same procedure can be used to test the normality of the residuals

$$e_i = y_i - \left(a + bx_i\right) \quad i = 1,\ldots,n$$

from a regression (see Section 9.6.3) assuming uniformity of variance of the residuals over the range of the independent variable. When calculating the test statistic AD, define

$$Z_{(i)} = e_{(i)}/s_y \quad i = 1,\ldots,n$$

where $e_{(i)}$, $i = 1,\ldots,n$ are the ordered residuals from smallest to largest and s_y is the root mean square error of the regression defined in Section 9.6.3.1. The justification for this procedure may be found in Reference 9.6.1.2(c).

9.6.1.3 ***Normal Probability Plot*** — To graphically illustrate the degree to which a normal distribution fits a set of data, the use of arithmetic probability paper is recommended. Logarithmic probability paper may be used to determine whether the distribution of data could be made normal by logarithmic transformation. One axis is scaled in units of the property measured, and the other is a nonlinear scale of probability.

The rank of each point selected for plotting is equal to the number of lower test points plus plotted point plus one half the number of other points equal to plotted point. Cumulative probability (P), in percent, is equal to the rank times 100, divided by one more than the total number of test points:

$$P\ (\text{in percent}) = \frac{(\text{rank})(100)}{n+1} \qquad [9.6.1.3]$$

* The standard normal distribution function F_o is that function such that $F_o(x)$ is equal to the area under the standard normal curve to the left of the value x.

The measured value of each test point is plotted versus its cumulative probability and a straight line is drawn to represent the normal distribution. This line may be established by plotting any two points from the normal distribution curve for $\overline{X}$ and s (for example, $\overline{X}$ - 3s at 0.13 percent probability, and $\overline{X}$ + 3s at 99.87 percent probability) and connecting these two points.

The plotted points should finally be compared with the line to determine whether there appears to be a reasonably good fit. With sample sizes on the order of 100 test points, only those points lying between about 10 and 90 percent probability should be considered in making this evaluation. With sample sizes of 1000 test points, these limits can be extended to about 1 and 99 percent.

If normal probability paper is unavailable, a normal probability plot may be formed by plotting the measured value of each test point versus $\overline{X} + s\,F_o^{-1}$ (P/100) where F_o^{-1} is the inverse standard normal cumulative distribution function.* The line representing the fitted normal distribution is the line passing through the points with equal horizontal and vertical coordinates. If the horizontal axis is labeled with cumulative probabilities (P values) rather than F_o^{-1} (P/100) values, the plot will be identical to a plot formed on normal probability paper.

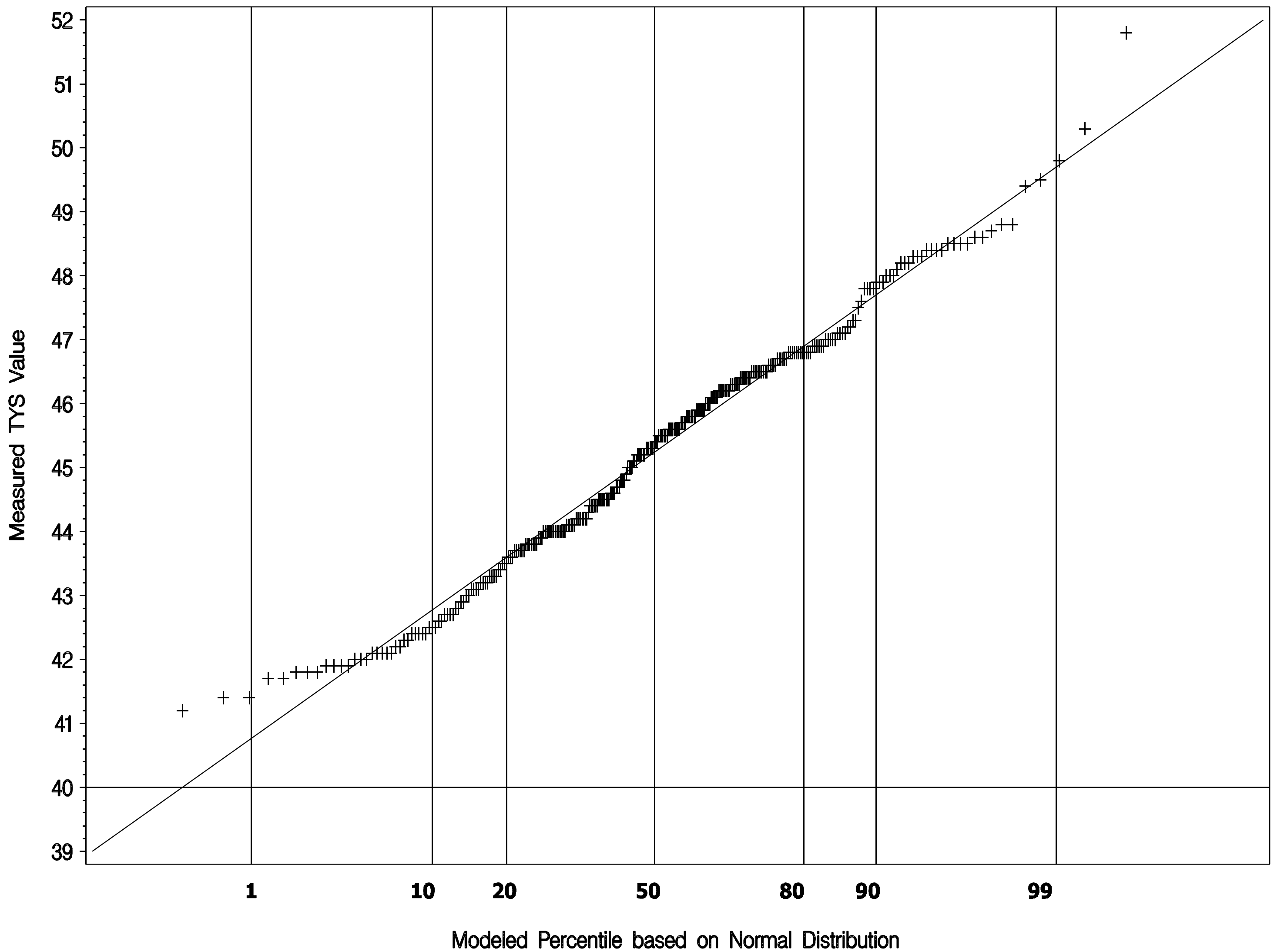
Figure 9.6.1.3 illustrates the use of a normal probability plot on Alclad 2524-T3 Aluminum Alloy Sheet and Plate data in the 0.063-0.128 inch thickness range. There are 309 measured test values with $\overline{X}$ = 45.24013 and s = 1.923135. There appears to be a systematic departure from the model (the measured values are higher than expected) in both tails, suggesting that the distribution of the measured values departs from a normal distribution. This model was rejected by the Anderson-Darling test for normality.

9.6.1.4 ***Modified "Anderson-Darling" Test for Weibullness*** — The "Anderson-Darling" test for three-parameter Weibullness is used to determine whether the curve which fits a given set of data can be approximated by a three-parameter Weibull curve. The essence of the test is a numerical comparison of the cumulative distribution function for observed data with that for a fitted Weibull curve over the entire range of property being measured. This test differs from the original version of the Anderson-Darling test in that it emphasizes the lower tail. This method can be applied with complete or censored data.

The first two steps produce estimates of the parameters of a three-parameter Weibull distribution. Be sure to acknowledge the appropriate degree of censoring in computing the threshold, shape, and scale parameters as described in Sections 9.6.5.1 and 9.6.5.2. Using the procedure outlined in 9.6.5.1, compute the threshold for the goodness-of-fit test, τ_{50}. Then, using the method described in 9.6.5.2, compute the maximum likelihood estimates of the shape and scale parameters for $\{X_{(i)} - \tau_{50} : i=1,...,r\}$ where r equals n for the uncensored data and r represents the smallest integer greater than or equal to 4n/5 for 20 percent censoring and n/2 for 50 percent censoring. Denote these estimates by β_{50} and α_{50}, respectively. Calculate the (censored or uncensored) A-D statistic by the following steps. For i=1,...,r, let

$$F_i = 1 - \exp\left(- \left(\frac{X_{(i)} - \tau_{50}}{\alpha_{50}} \right)^{\beta_{50}} \right) ,$$

* The point F_0^{-1} (P/100) is that value such that the area under the standard normal curve to the left of F_o^{-1} (P/100) is P/100.



Vertical reference lines plotted at 1st, 10th, 20th, 50th, 80th, 90th, and 99th percentiles of fitted distribution
Horizontal reference line plotted at spec minimum, 40 ksi

Figure 9.6.1.3. Probability plot for a normal distribution fitted to a complete TYS data set for Alcad 2524-T3 aluminum alloy sheet in the 0.063-0.128 inch thickness range - rejected.

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let $F_{n+1} = 1$, and let

$$C_i = \frac{2i-1}{n}.$$

Define the A-D statistic as

$$AD = -\sum_{i=1}^{r} \left(C_i \ \ln F_i - 2F_i\right) + \frac{r^2}{n} \ln F_{r+1} - 2r \ F_{r+1} + \frac{n}{2} F_{r+1}^2 - \frac{n}{2} F_1^2.$$

If

$$AD \geq \begin{cases} 0.3951 + 4.186 \times 10^{-5}\ n & \text{(Uncensored)} \\ 0.2603 + 4.182 \times 10^{-5}\ n & \text{(20 percent censored)} \\ 0.1761 + 1.842 \times 10^{-5}\ n & \text{(50 percent censored)} \end{cases} \qquad [9.6.1.4]$$

one may conclude (at 5 percent risk of error) that the population from which the sample was drawn is not a three-parameter Weibull population. Otherwise, the hypothesis that the population is a three-parameter Weibull population is not rejected. Equation 9.6.1.4 was derived under the assumption that the threshold parameter is estimated, not known. For further information on this test procedure, see Reference 9.6.1.2(a).

9.6.1.5 ***Weibull Probability Plot*** — To graphically illustrate the degree to which a three-parameter Weibull distribution fits a set of data, the following procedure for creation of a Weibull probability plot is recommended. This method is appropriate for distributions estimated using censored or uncensored data. A method for displaying the fit using a distribution estimated by a backoff option is also described.

The rank of each point selected for plotting is the number of lower test points plus the plotted point plus one-half the number of other test points equal to the plotted point. Its cumulative probability, P (in percent), is equal to the rank multiplied by 100, divided by one more than the total number of test points:

$$P \ (\text{in percent}) = \frac{(\text{rank})(100)}{n+1}$$

The measured value of each test point is plotted versus F^{-1} (P/100) where

$$F^{-1}\ (P/100) = \tau_{50} + \alpha_{50}\left[-\ln\left(1 - (P/100)\right)\right]^{\frac{1}{\beta_{50}}}$$

and τ_{50}, α_{50}, and β_{50} are population parameter estimates obtained according to the procedures outlined in Section 9.6.5. A straight line is then drawn to represent the fitted Weibull distribution. This line may be established by plotting any two points with equal vertical and horizontal coordinates and drawing a line through these two points. The horizontal axis is then labeled with cumulative probabilities rather than F^{-1} values.

If the backoff option is used, the selected distribution can then be described as the best-fit distribution shifted by a small constant, $\tau_{backoff}$. In this case, the predicted values should also be shifted by the same constant. That is, plot the measured values versus

$$F^{-1}(P/100) - \tau_{backoff} \quad .$$

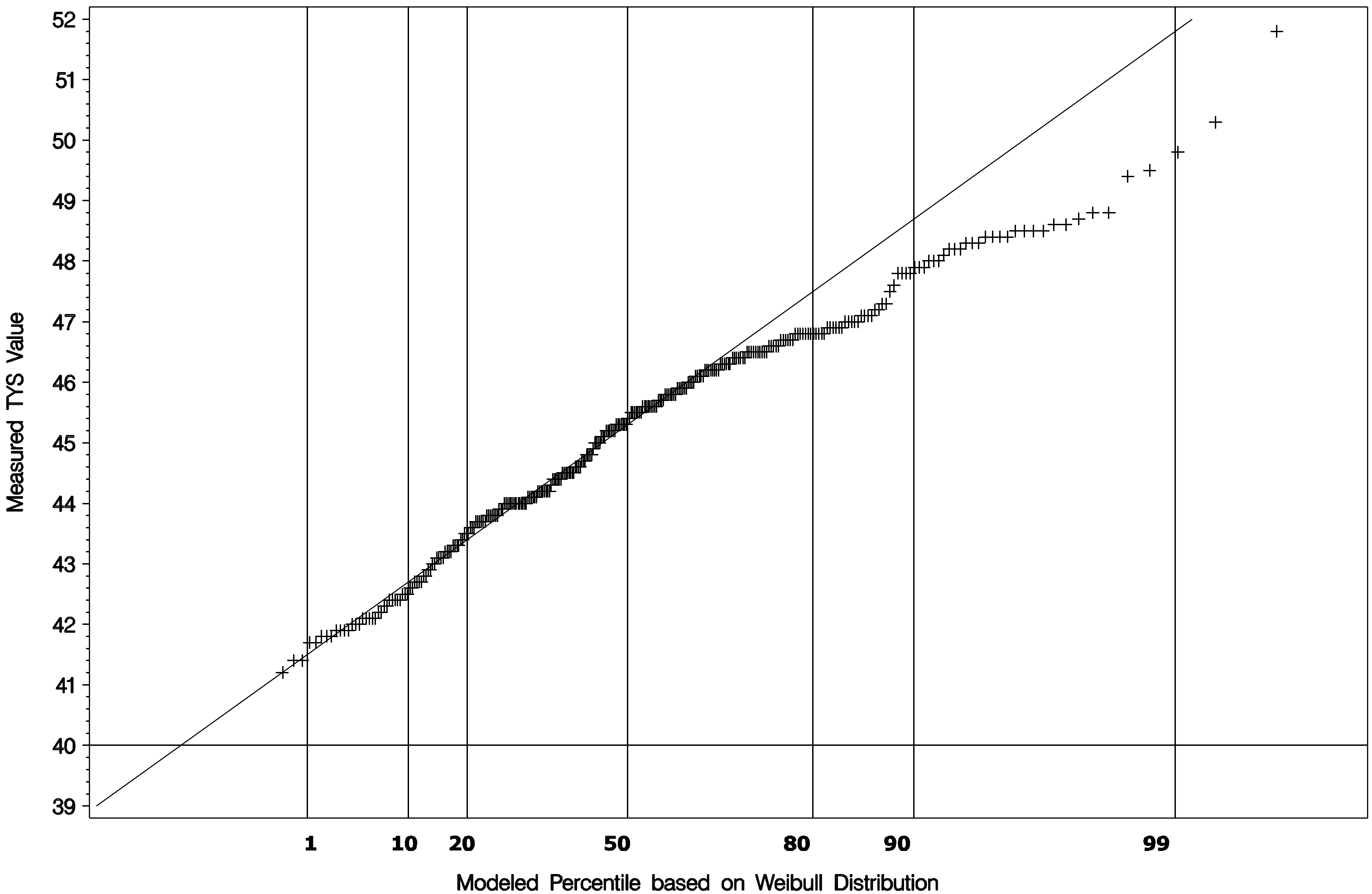
The plotted points should finally be compared with the line to determine whether there appears to be a reasonably good fit. With sample sizes on the order of 100 test points, only those points lying between about 10 and 90 percent probability should be considered in making this evaluation. With sample sizes of 1000 test points, these limits can be extended to about 1 and 99 percent. If the distribution was estimated using a method for censored data, then only the uncensored portion of the data used to estimate the distribution should be considered when assessing lack of fit. For instance, if the 20 percent censoring method is selected for use by the sequential Weibull method, then only the lower 80 percent of the data should be examined for agreement with the line of best fit. If the backoff option was used, then only deviations where the data fall below the fitted line should be considered as departures.

Figure 9.6.1.5(a) illustrates the use of a Weibull probability plot on Alclad 2524-T3 Aluminum Alloy Sheet and Plate data in the 0.063-0.128 inch thickness range. This is a probability plot based on a Weibull distribution estimated using the 50 percent censoring method. The estimates of the threshold, scale, and shape parameters based on 50 percent censoring are 40.87, 5.26, and 2.09, respectively. Notice that the lower tail does not exhibit serious departures from the model, but significant departures are apparent in the upper tail. But, as mentioned above, only the lower 50 percent of the data should be included in an assessment of this probability plot, because the rest are not used in fitting the model. The model estimated by this method was accepted by the Anderson-Darling test for Weibullness.

Figures 9.6.1.5(b) and 9.6.1.5(c) illustrate the value of the backoff method and the construction and interpretation of the associated probability plots. Alclad 2524-T3 Aluminum Alloy Sheet and Plate tensile yield data in the 0.250 – 0.310 inch thickness range is used for illustration. There are 1202 measured test values. The estimates of the threshold, scale, and shape parameters of the best-fit Weibull distribution, based on the uncensored data, are 40.00, 3.50, and 2.62, respectively. The departures from the reference line in Figure 9.6.1.5(b) suggest that this Weibull distribution does not provide a good fit for the measured values, and it was rejected by Anderson-Darling test for Weibullness.

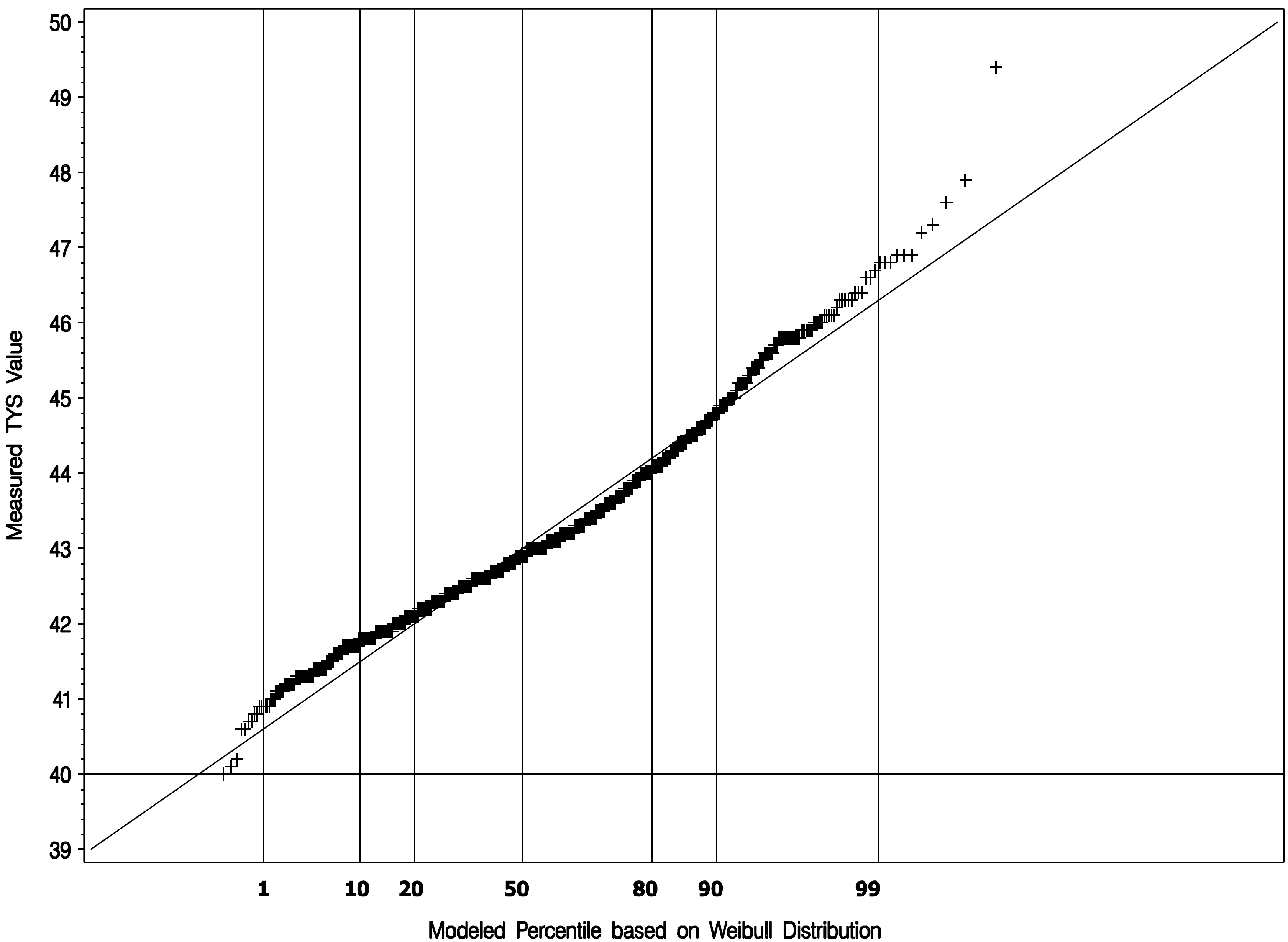
Figure 9.6.1.5(c) shows a probability plot of the same data, using the distribution estimated with the backoff option of the sequential Weibull procedure, which identified a backoff of 0.2 ksi. The only difference between the two plots is that the predicted values in Figure 9.6.1.5(b) are shifted 0.2 ksi to the left in Figure 9.6.1.5(c). Although the curve of data in Figure 9.6.1.5(c) is further away (on average) from the y=x reference line than the curve of data in Figure 9.6.1.5(b), only negative deviations from the reference line are recognized in the Anderson-Darling goodness-of-fit test for a distribution estimated by the backoff method. In Figure 9.6.1.5(c), only a small proportion of the data in the very middle of the distribution are below the predicted values, resulting in an insignificant departure from Weibullness.

9.6.1.6 *Identifying Proper Backoff for Weibull Method* — Begin with the estimates τ_{50}, α_{50}, and β_{50} obtained according to the procedures outlined in Section 9.6.5. Let $F_\tau(x)$ represent the cumula-tive distribution function of the three-parameter Weibull distribution with threshold parameter τ, and scale and shape parameters, α_{50} and β_{50}, respectively:



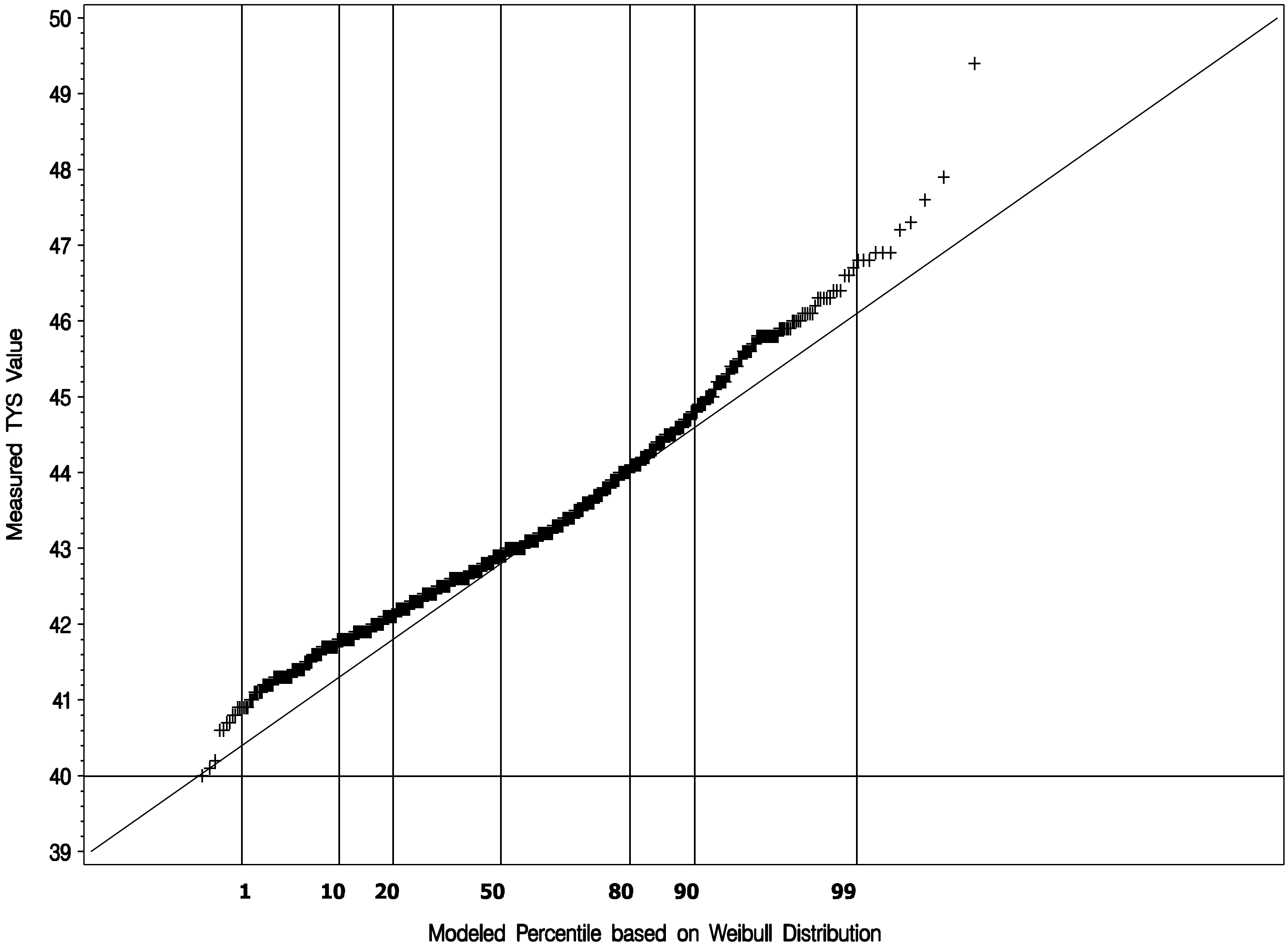
Vertical reference lines plotted at 1st, 10th, 20th, 50th, 80th, 90th, and 99th percentiles of fitted distribution
Horizontal reference line plotted at spec minimum, 40 ksi

Figure 9.6.1.5(a). Probability plot for a Weibull distribution fitted with 50 percent censored TYS data for Alcad 2524-T3 aluminum alloy sheet in the 0.063-0.128 inch thickness range - accepted.



Vertical reference lines plotted at 1st, 10th, 20th, 50th, 80th, 90th, and 99th percentiles of fitted distribution
Horizontal reference line plotted at spec minimum, 40 ksi

Figure 9.6.1.5(b). Probability plot for a Weibull distribution fitted to a complete TYS data set for Alcad 2524-T3 aluminum alloy plate in the 0.250-0.310 inch thickness range - rejected.



Vertical reference lines plotted at 1st, 10th, 20th, 50th, 80th, 90th, and 99th percentiles of fitted distribution
Horizontal reference line plotted at spec minimum, 40 ksi

Figure 9.6.1.5(c). Probability plot for a Weibull distribution fitted to complete TYS data for Alcad 2524-T3 aluminum alloy plate in the 0.250-0.310 inch thickness range using 0.2 ksi backoff - accepted.

$$F_\tau(x) = 1 - \exp\left(-\left(\frac{x-\tau}{\alpha_{50}}\right)^{\beta_{50}}\right).$$

Define the special “backoff” Anderson Darling statistic by

$$ADB(\tau) = n \sum_{i=1}^{n} \left[\left(\frac{i}{n}\right)^2 (\ln b_i - \ln a_i) - \frac{2i}{n}(b_i - a_i) + \frac{1}{2}(b_i^2 - a_i^2)\right],$$

where $a_i = \min\{F_\tau(x_{(i)}), i/n\}$, $b_i = \min\{F_\tau(x_{(i+1)}), i/n\}$ for $i < n$, and $b_n = 1$. Let $\tau_{backoff}$ be the smallest value among 0.1, 0.2, 0.3, 0.4, and 0.5 such that

$$ADB(\tau_{50} - \tau_{backoff}) < 0.0359 + 1.2 \times 10^{-5}\, n\,. \qquad [9.6.1.5]$$

If none of the five values satisfies Equation 9.6.1.5, the backoff procedure cannot be used to compute T_{99} and T_{90}. Otherwise, $\tau_{backoff}$ is subtracted from T_{99} and T_{90} as calculated from the complete sample.

9.6.1.7 *Anderson-Darling Test for Pearsonality* – This section describes a test to determine whether data from a population are satisfactorily described by the Pearson Type III (or gamma) distribution. First compute estimates of the population mean, standard deviation, and skewness (denoted by $\overline{X}$, S, and q), as described in Section 9.2.7.2. Then calculate the following Anderson-Darling statistic:

$$AD = -\sum_{i=1}^{n}\left[\frac{(2i-1)}{n}\ln\left(F_{\bar{X},S,q}(X_{(i)})\right) - 2F_{\bar{X},S,q}(X_{(i)})\right] - \frac{3n}{2}$$

where

$$F_{\mu,\sigma,q}(x) = \begin{cases} H\left[\dfrac{4}{q}\left(\dfrac{2}{q}+\dfrac{x-\mu}{\sigma}\right)\right] & q > 0.1265 \\[2ex] 1 - H\left[\dfrac{4}{q}\left(\dfrac{2}{q}+\dfrac{x-\mu}{\sigma}\right)\right] & q < -0.1265 \\[2ex] \Phi\left\{\left[\sqrt[3]{\dfrac{\frac{4}{q}\left(\frac{2}{q}+\frac{x-\mu}{\sigma}\right)}{\frac{8}{q^2}}} - 1 + \dfrac{2}{9\cdot\frac{8}{q^2}}\right]\Bigg/\sqrt{\dfrac{2}{9\cdot\frac{8}{q^2}}}\right\} & 0.025 < q \le 0.1265 \\[2ex] 1 - \Phi\left\{\left[\sqrt[3]{\dfrac{\frac{4}{q}\left(\frac{2}{q}+\frac{x-\mu}{\sigma}\right)}{\frac{8}{q^2}}} - 1 + \dfrac{2}{9\cdot\frac{8}{q^2}}\right]\Bigg/\sqrt{\dfrac{2}{9\cdot\frac{8}{q^2}}}\right\} & -0.1265 \le q < 0.025 \\[2ex] \Phi\left(\dfrac{x-\mu}{\sigma}\right) & |q| \le 0.025 \end{cases}$$

H(x) is the cumulative distribution function of a chi-square distribution with $8/q^2$ degrees of freedom. Note that F(x) is the cumulative distribution function of a chi-square distribution with $8/q^2$ degrees of freedom when $q > 0.1265$, and a standard normal distribution when $|q| \leq 0.025$. Because of numerical computing inconsistencies for large degrees of freedom, a normal approximation to the chi-square distribution is recommended for 0.025 < *q* # 0.1265 .

If the *AD* is greater than the critical value of

$$0.3167 + 0.034454 \cdot \ln(n) \cdot [\exp(q) - 1]^2,$$

then the data are rejected by the Anderson-Darling test for Pearsonality.

9.6.1.8 ***The Pearson Backoff Option*** – If the data are rejected by the Pearson AD test, the backoff method may be applied. The following formula should be used to calculate the AD statistic of the backoff method:

$$AD_{backoff}(\mu) = \frac{1}{n}\sum_{i=1}^{n} i^2 \left[\ln(b_{i+1,i}) - \ln(b_{i,i})\right] - 2\sum_{i=1}^{n} i(b_{i+1,i} - b_{i,i}) + \frac{n}{2}\sum_{i=1}^{n}(b_{i+1,i}{}^2 - b_{i,i}{}^2)$$

where $b_{i,j} = \min\left[F_{\mu,S,q}(x_{(i)}), \frac{j}{n}\right]$ for j<n, $b_{n,n} = F_{\mu,S,q}(x_{(n)})$, and $b_{n+1,n}=1$. (Notice that this formula has an argument representing the assumed mean of the distribution being tested against.)

Calculate $AD_{backoff}(\overline{X} - \tau)$ for J equal to 0.1, 0.2, 0.3, 0.4, and 0.5. If any of these values is below the critical value of

$$0.03238 + 0.00001795 \cdot \ln(n)^2 \cdot [\exp(q) + 0.2355]^2,$$

then $J_{backoff}$, is defined as the smallest of these τ's satisfying the inequality. (Note: In calculating the backoff, if q is negative and $\tau_{backoff} > \overline{X} - 2 \cdot S / Q - X_{(n)}$, then the backoff method cannot be applied. *S* and *Q* are defined in Section 9.2.7.2.)

If a backoff is identified, then T_{99} and T_{90} should be calculated by the following formulas:

$$T_{99} = \overline{X} - k_{99}(q, n) \cdot S - \tau_{backoff}$$
$$T_{90} = \overline{X} - k_{90}(q, n) \cdot S - \tau_{backoff}$$

where $k_{90}(q, n)$ and $k_{99}(q, n)$ are defined in Section 9.2.7.2.

9.6.1.9 Pearson Probability Plot — To graphically illustrate the degree to which a Pearson Type III (or gamma) distribution fits a set of data, the following procedure for creation of a Pearson probability plot is recommended. This method is appropriate for distributions estimated using uncensored data. A method for displaying the fit using a distribution estimated by a backoff option is described Section 9.6.1.5.

The rank of each point selected for plotting is the number of lower test points plus the plotted point plus one-half the number of other test points equal to the plotted point. Its cumulative probability, P (in percent), is equal to the rank multiplied by 100, divided by one more than the total number of test points:

$$P \text{ (in percent)} = \frac{(\text{rank})(100)}{n + 1}$$

The measured value of each test point is plotted versus F^{-1} (P/100) where

$$F^{-1}(P/100) = \begin{cases} \overline{X} + s \cdot \left[\dfrac{q}{4} \cdot H^{-1}(P/100) - \dfrac{2}{q} \right] & \text{when } q > 0.1265 \\[2ex] \overline{X} + s \cdot \left[\dfrac{q}{4} \cdot H^{-1}\left[1 - (P/100)\right] - \dfrac{2}{q} \right] & \text{when } q < -0.1265 \\[2ex] \overline{X} + s \cdot \dfrac{2}{q} \cdot \left\{ \left[\sqrt{\dfrac{2}{9 \cdot \frac{8}{q^2}}} \cdot F_o^{-1}(P/100) + 1 - \dfrac{2}{9 \cdot \frac{8}{q^2}} \right]^3 - 1 \right\} & 0.025 < q \le 0.1265 \\[2ex] \overline{X} + s \cdot \dfrac{2}{q} \cdot \left\{ \left[\sqrt{\dfrac{2}{9 \cdot \frac{8}{q^2}}} \cdot F_o^{-1}(1 - P/100) + 1 - \dfrac{2}{9 \cdot \frac{8}{q^2}} \right]^3 - 1 \right\} & -0.1265 \le q < -0.025 \\[2ex] \overline{X} + s \cdot F_o^{-1}(P/100) & |q| \le 0.025 \end{cases}$$

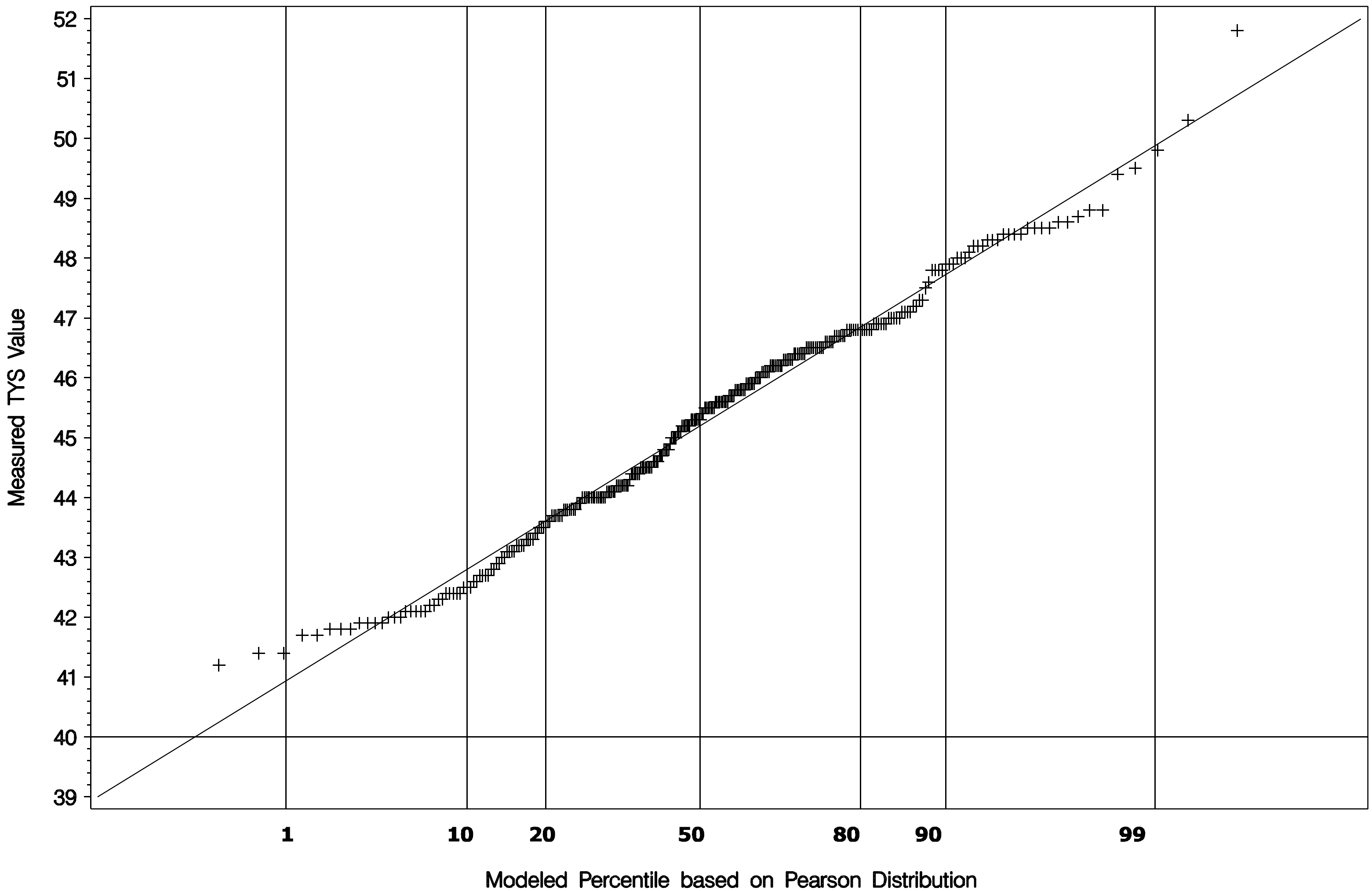
and $\overline{X}$, s, and q are population parameter estimates obtained according to the procedures outlined in Section 9.2.7.2. H^{-1} is the cumulative distribution function of a chi-square distribution with $8/q^2$ degrees of freedom and F_o^{-1} is the inverse standard normal cumulative distribution function. A straight line is then drawn to represent the fitted Pearson distribution. This line may be established by plotting any two points with equal vertical and horizontal coordinates and drawing a line through these two points. The horizontal axis is then labeled with cumulative probabilities (P or P/100) rather than F^{-1} values.

If the backoff option is used, the selected distribution can then be described as the best-fit distribution shifted by a small constant, $\tau_{backoff}$. In this case, the predicted values should also be shifted by the same constant. That is, plot the measured values versus

$$F^{-1}(P/100) - \tau_{backoff} \quad .$$

The plotted points should finally be compared with the line to determine whether there appears to be a reasonably good fit. If the backoff option is used, then only deviations where the data fall below the fitted line should be considered as relevant.

Figure 9.6.1.9(a) illustrates the use of a Pearson probability plot on Aluminum Alloy Sheet and Plate data in the 0.063-0.128 inch thickness range. The estimates of the mean, standard deviation, and skewness parameters are 45.24, 1.92, and 0.12, respectively. There appears to be a systematic departure from the model (the measured values are higher than expected) in both tails, suggesting that the distribution of the measured values is not well approximated by a Pearson distribution. Appropriately, this model was rejected by the A-D test for Pearsonality.



Vertical reference lines plotted at 1st, 10th, 20th, 50th, 80th, 90th, and 99th percentiles of fitted distribution
Horizontal reference line plotted at spec minimum, 40 ksi

Figure 9.6.1.9(a). Probability plot for a Pearson distribution fitted to a complete TYS data set for Alcad 2524-T3 aluminum alloy sheet in the 0.063-0.128 inch thickness range - rejected.

Figure 9.6.1.9(b) shows a probability plot for the same data, using the distribution estimated with the backoff option of the sequential Pearson procedure, which identified a backoff of 0.2 ksi. The only difference between the two plots is that the predicted values in Figure 9.6.1.9(a) are shifted 0.2 ksi to the left in Figure 9.6.1.9(b). Although the curve of data in Figure 9.6.1.9(b) is further away (on average) from the y=x reference line than the curve of data in Figure 9.6.1.9(a), only negative deviations from the reference line are recognized in the A-D goodness-of-fit test for a distribution estimated by the backoff method. In Figure 9.6.1.9(b), only a small proportion of the data are below the predicted values, resulting in an insignificant deviation. The "backoff" model was accepted by the A-D test.

9.6.2 TESTS OF SIGNIFICANCE

9.6.2.1 ***Introduction*** — A test of significance is employed to make a decision on a statistical basis. In this section, three tests ("F" test, "t" test, and k-sample Anderson-Darling test) are described for use in determining whether the populations from which two or more samples are drawn are identical.

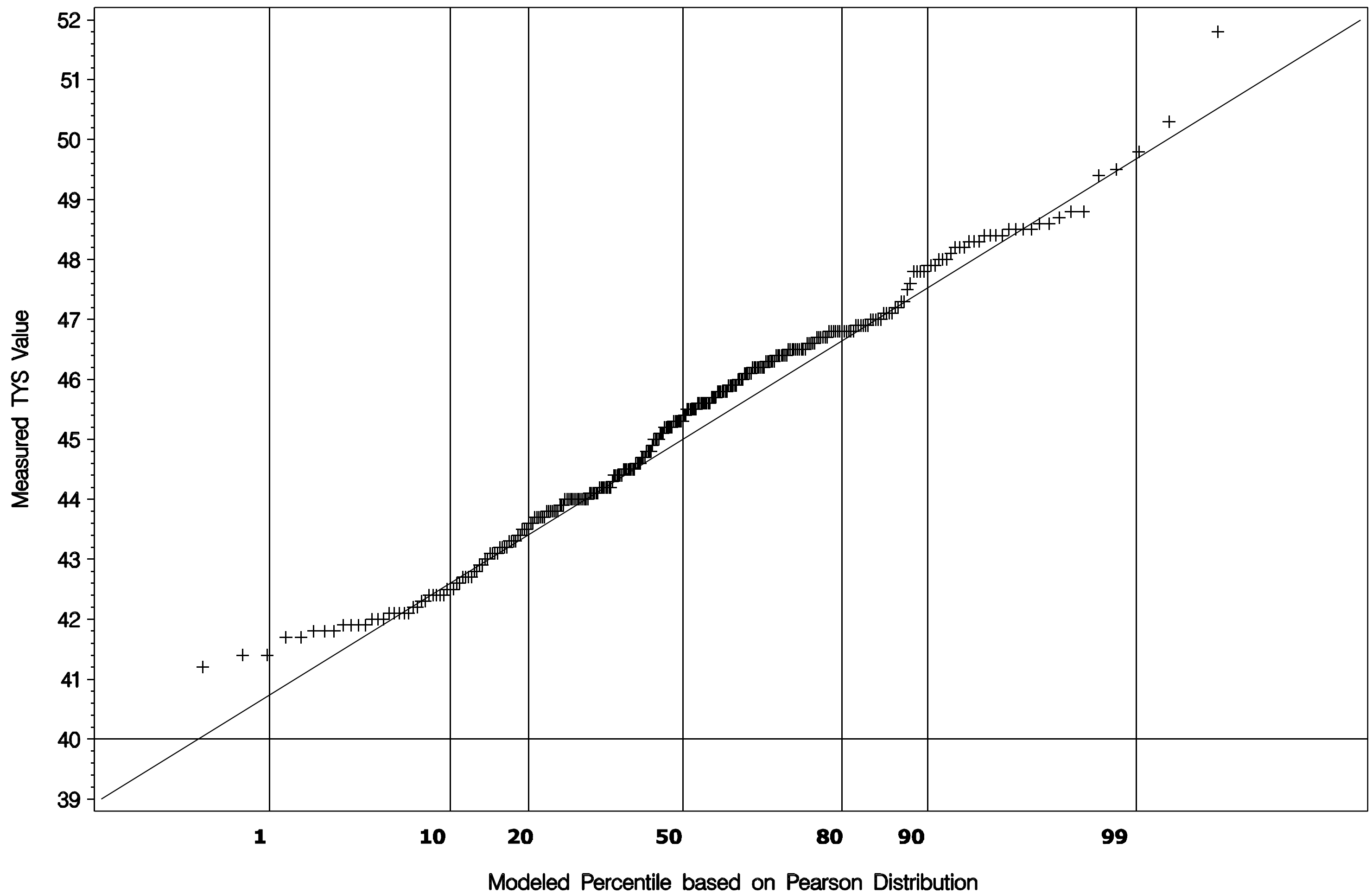
Assuming an underlying normal distribution, "F" and "t" tests may be used in the case of two samples. The "F" test is used first to determine whether the two sample variances differ significantly or not (with a 5 percent risk of error). If the two sample variances do not differ significantly, the "t" test is used to determine whether the two sample means differ significantly. If either the two sample variances or the two sample means differ significantly (with a 5 percent risk of error), one may conclude (with a 9.75 percent joint risk error) that the populations from which the two samples were drawn are not identical. Otherwise, the hypothesis that the two populations are identical is not rejected. The tests given are exact when:

(1) The observations within each sample are taken randomly from a single population of possible observations, and

(2) The characteristic measured is normally distributed within this population.

To carry out a similar procedure without requiring the assumption of an underlying normal distribution, or if three or more samples are to be compared, the k-sample Anderson-Darling test should be employed. This test is a nonparametric procedure and simply tests the hypothesis that populations from which the samples are drawn are identical.

9.6.2.2 ***Definitions*** — Location and dispersion parameters are defined in Section 9.2.2.3, and these terms are used in various parts of the Guidelines. The following definitions apply specifically to tests in this section:



Vertical reference lines plotted at 1st, 10th, 20th, 50th, 80th, 90th, and 99th percentiles of fitted distribution
Horizontal reference line plotted at spec minimum, 40 ksi

Figure 9.6.1.9(b). Probability plot for a Pearson distribution fitted to complete TYS data for Alcad 2524-T3 aluminum alloy plate in the 0.063-0.128 inch thickness range using 0.2 ksi backoff - accepted.

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Significance Level (As Used Here) — Risk of concluding that two samples were drawn from different populations when, in fact, they were drawn from the same population. A significance level of $\alpha = 0.05$ is employed through these Guidelines.*

Confidence Interval Estimate — Range of values, computed with the sample that is expected to include the population variance or mean.

Degrees of Freedom — Number of independent comparisons afforded by a sample.

9.6.2.3 *The F Test* — The F test is used to determine whether the strength of two products differs with regard to variability.

Consider two products, A and B. These might represent two different processes, thickness ranges, or test directions. The statistics for the samples drawn from these products are:

	Product A	Product B
Sample size	n_A	n_B
Sample standard deviation	s_A	s_B
Sample mean	$\bar{X}_A$	$\bar{X}_B$

F is the ratio of the two sample variances, thus,

$$F = s_A^2/s_B^2 \qquad [9.6.2.3]$$

If the true variances of Products A and B are identical at a significance level of $\alpha = 0.05$, F should lie within the interval defined by

$F_{0.975}$ (for n_A - 1 and n_B - 1 degrees of freedom),

and

$1/F_{0.975}$ (for n_B - 1 and n_A - 1 degrees for freedom).**

If F does not lie within this interval, it can be concluded that the two products differ with regard to their variability. Values of $F_{0.975}$ are presented in Table 9.6.4.4.

9.6.2.3.1 *Example of Test Computation* — The following sample statistics are reported:

	Product A	Product B
Sample size	20	30
Sample standard deviation, ksi	4.0	5.0
Sample mean, ksi	100.0	102.0

* This is appropriate, since a confidence level 1 - α = 0.95 is used in establishing T_{99} and T_{90} values.

** Since a two-sided interval is being defined for the population variance, the fractile of the F distribution corresponding to 1 - $\alpha/2$ should be used, i.e., $F_{0.975}$.

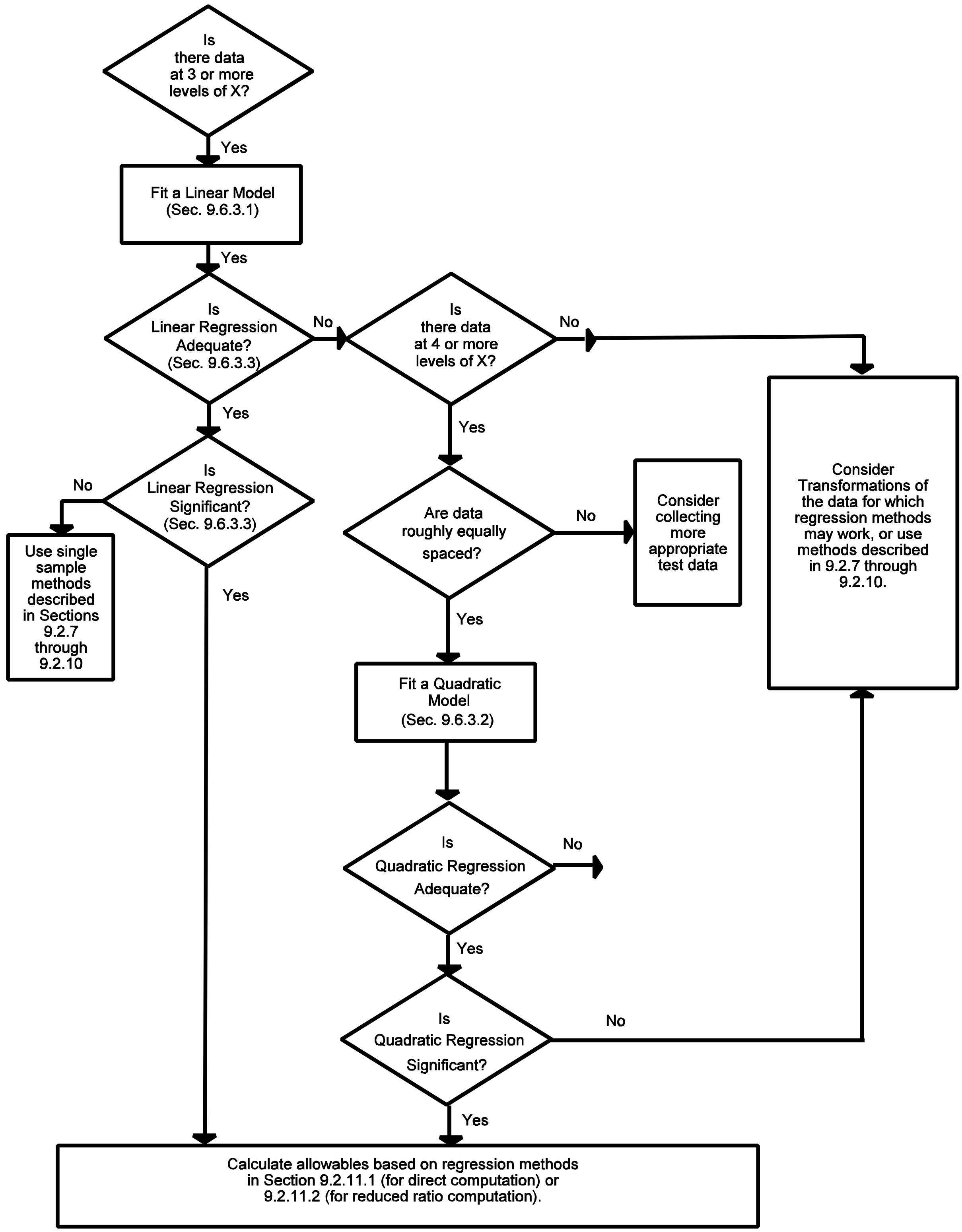

Figure 9.6.3. General procedures for performing a regression analysis in order to calculate design allowables.

$$y = \alpha + \beta x + \epsilon \qquad [9.6.3.1(a)]$$

where

x = independent variable
y = dependent variable
α = true intercept of the regression equation
β = true slope of the regression equation
ϵ = measurement or experimental error by which y differs from the ideal linear relationship.

Aside from the error term, ϵ, this is the equation of a straight line. The parameter α determines the point where this line intersects the y-axis, and the β represents its slope. The variable x and y may represent either direct measurements or some transformation measurements of the characteristics under consideration.

Knowing or assuming such an approximate linear relationship, the problem becomes one of estimating the parameters α and β of the regression equations. It is necessary to have a random sample consisting of n pairs of observations, which is denoted by $(x_1, y_1),(x_2, y_2),..., (x_n, y_n)$. Such a sample can be represented graphically by n points plotted on a coordinate system, in which x is plotted horizontally and y vertically. A subjective solution can be obtained by drawing a line that, by visual inspection, appears to fit the points satisfactorily. An objective solution is given by the method of least squares.

The method of least squares is a numerical procedure for obtaining a line having the property that the sum of squares of vertical deviations of the sample points from this line is less than that for any other line. In this analysis, the least-squares line is represented by the equation

$$\hat{y} = a + bx \quad , \qquad [9.6.3.1(b)]$$

in which

$\hat{y}$ = predicted value of y for any value of x
a and b = estimates of the parameters α and β in the true regression equation obtained by the least squares method presented below.

It can be shown with the aid of calculus that the values of a and b that minimize the sum of squares of the vertical deviations are given by the formulas:

$$a = \frac{\Sigma y - b\Sigma x}{n} \qquad [9.6.3.1(c)]$$

$$b = \frac{S_{xy}}{S_{xx}} \qquad [9.6.3.1(d)]$$

where

$$S_{xy} = \Sigma xy - \frac{\Sigma x \; \Sigma y}{n} \quad , \qquad [9.6.3.1(e)]$$

and

$$s_y = \sqrt{\frac{\sum (y-\hat{y})^2}{n-3}} \qquad [9.6.3.2(d)]$$

where $\hat{y}$ is the predicted value of y defined above. This quantity is an estimate of the standard deviation of the distribution of y about the regression curve. A convenient computational formula for s_y is

$$s_y = \sqrt{\left(\sum Y^2 - b\sum X_1 Y - c\sum X_2 Y\right) / (n-3)} \qquad [9.6.3.2(e)]$$

The quantity $R^2 = 1-(n-3)\, s_y^2 / \Sigma Y^2$ measures the proportion of total variation in the y data, about its average, that is explained by the regression. An R^2 equal to 1 indicates that the regression model describes the data perfectly, which is rare in practice. R^2 provides a rough idea of how well the data are described by a quadratic regression.

Another quantity, Q, is required to compute allowables by quadratic regression analysis. Q is defined as

$$Q = q_1 + 2q_2 x_o + (2q_3 + q_4)\, x_o^2 + 2q_5\, x_o^3 + q_6\, x_o^4 \qquad [9.6.3.2(f)]$$

where x_0 is the value of the independent variable for which the allowable is being calculated and q_1, q_2, q_3, q_4, q_5 and q_6 are defined as:

$q_1 = k\,[\,ce - d^2]$, $q_2 = k\,[\,cd - be]$, $q_3 = k\,[\,bd - c^2]$,
$q_4 = k\,[\,ae - c^2]$, $q_5 = k\,[\,bc - ad]$, and $q_6 = k\,[\,ac - b^2]$

where[*]

$a = n$, $b = \Sigma\, x_i$, $c = \Sigma\, x_i^2$, $d = \Sigma\, x_i^3$, $e = \Sigma\, x_i^4$, and $k = [\,(ace + 2bcd) - (\,c^3 + ad^2 + b^2 e)\,]^{-1}$.

9.6.3.3 ***Tests for Adequacy of a Regression*** — It is possible that the relationship between the dependent variable y and the independent variable x may not be well approximated by the chosen model (linear or quadratic). In that case, the predicted values, modeled by a line or a quadratic curve, would not "fit" the data very well. It is also possible that the relationship between x and y, although well described by the chosen model, is not very strong. That is, there may not be much change in the y values over the range of x considered. This is measured by the "significance" of the regression. Both the lack of fit and the significance of a linear regression equation can be evaluated through an analysis of variance as described in this section.

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[*] Although it is not necessary for the computations, the values q_1, q_2, q_3, q_4, q_5, and q_6 represent elements

of the inverted matrix $(X'X)^{-1} = \begin{bmatrix} q_1 & q_2 & q_3 \\ q_2 & q_4 & q_5 \\ q_3 & q_5 & q_6 \end{bmatrix}$, where $X'X = \begin{bmatrix} n & \sum x_i & \sum x_i^2 \\ \sum x_i & \sum x_i^2 & \sum x_i^3 \\ \sum x_i^2 & \sum x_i^3 & \sum x_i^4 \end{bmatrix}$.

To evaluate the adequacy of a regression model requires satisfying two conditions. First, it is necessary that there are multiple observations at one or more values of the independent variable x. Second, in the case of a linear regression, there must be three or more distinct x values; in the case of a quadratic regression, there must be four or more distinct x values.

The analysis of variance for testing lack of fit and significance of regression is based on the assumption that the measurement errors, ε_i, in the relationship between y_i and x_i (see 9.6.3.1(a) and 9.6.3.2(a1)) are independent and normally distributed with an overall mean of zero and a constant variance of σ^2. Assuming uniformity of variance of measurement errors over the range of the independent variable, the normality assumption concerning unobservable ε_i can be checked by performing the Anderson-Darling test for normality on the observed residuals

$$e_i = y_i - \hat{y}_i,$$

i=1,…, n, where

$$\hat{y}_i = a + bx_i$$

in the case of linear regression, and

$$\hat{y}_i = a + bx_i + cx_i^2$$

in the case of quadratic regression. See Sections 9.6.3.1 and 9.6.3.2 for details on the computation of a, b, and c, and see Section 9.6.1.2 for details on the Anderson-Darling test for normality. By plotting the residuals, e_i, against the respective x_i, an informal check on the assumption of constant variance is possible as well. In such a plot, residuals should vary approximately equally over the range of x_i values.

The analysis of variance table for testing lack of fit and significance of a linear regression is shown below. In this table, n represents the total number of data points for which x and y are available, k represents the number of distinct x values. Formulas for calculating the terms provided in the table are described below.

	Degrees of Freedom				
Source of Variation	Linear	Quadratic	Sum of Squares, SS	Mean Squares, MS	F_{calc}
Regression	1	2	SSR	MSR	F_1
Error	n-2	n-3	SSE	MSE	
Lack of Fit	k-2	k-3	SSLF	MSLF	F_2
Pure Error	n-k	n-k	SSPE	MSPE	
Total	n-1	n-1	SST		

The sums of squares (SS terms) for the Regression, Error, and Total lines of the analysis of variance table are calculated using the following:

$$SSR = \sum (\hat{y}_i - \bar{y})^2$$
$$SST = \sum (y_i - \bar{y})^2$$
$$SSE = \sum (y_i - \hat{y}_i)^2$$

To calculate the sums of squares for lack of fit (SSLF) and pure error (SSPE) requires a relabeling of the data, ordered by x value. To this point, the measured values y_i have been arbitrarily ordered. For these calculations, let Y_{uj} represent the j^{th} data value at the u^{th} x level, and let n_u represent the number of data values at the u^{th} x level. Let

$$\overline{Y}_u = \sum_{j=1}^{n_u} Y_{uj} / n_u$$

Also, let

$$\hat{Y}_{uj} = \hat{y}_i ,$$

or the predicted y value corresponding to the x value paired with Y_{uj}. (Notice that

$$\hat{Y}_{u1} = \hat{Y}_{u2} = \hat{Y}_{u3} = \cdots = \hat{Y}_{un_u} ,$$

because each of these y values have the same x value paired with it.)

Then

$$SSLF = \sum_{u=1}^{k} \sum_{j=1}^{n_u} \left(\overline{Y}_u - \hat{Y}_{uj} \right)^2 ,$$

and

$$SSPE = SSE - SSLF.$$

The sums of squares are then divided by their respective degrees of freedom to compute mean squares follows:

Mean Square	Linear Regression	Quadratic Regression
MSR	SSR	SSR/2
MSE	SSE/(n-2)	SSE/(n-3)
MSLF	SSLF/(k-2)	SSLF/(k-3)
MSPE	SSPE/(n-k)	SSPE/(n-k)

These mean squares are used to compute two F statistics which test for lack of fit and significance of regression. (Note: If the requirements described at the beginning of this section are not satisfied, then it is not possible to test for lack of fit.)

The two F statistics, F_1 and F_2, are defined as ratios of the mean squares as specified below:

$$F_1 = MSR/MSE$$
$$F_2 = MSLF/MSPE.$$

F_2 and Table 9.6.4.9 are used to test for lack of fit. If F_2 is greater than the 95^{th} percentile of the F distribution with k – 2 numerator degrees of freedom (k – 3 for quadratic regression) and n – k denominator degrees of freedom (from Table 9.6.4.9), then there is significant lack of fit. In this case it may be concluded (with a 5 percent risk of error) that linear regression does not adequately describe the relationship between x and y. Otherwise, lack of fit can be considered insignificant and the chosen model can be assumed.

If lack of fit is not significant, the significance of regression may be tested using F_1 and Table 9.6.4.9. If F_1 is greater than the 95th percentile of the F distribution with 1 numerator degree of freedom (2 for quadratic regression) and n – 2 denominator degrees of freedom (n – 3 for quadratic regression), then regression is significant and the selected model may be assumed. Otherwise, regression is not significant and x is considered to have little or no predictive value for y.

9.6.3.4 ***Testing for Equality of Several Regressions*** — The procedure presented in this section is designed to test the hypothesis that the true regression equations corresponding to two or more independent data sets are equal (linear or quadratic). It is appropriately applied to test the equality of several regressions in determining whether corresponding data sets should be combined for the purpose of calculating design allowables. To test k regressions for equality, the following procedure should be performed.

Perform separate regression analyses for each data set. The same model form should be used in all regressions (all linear or all quadratic). Add error sum of squares (SSE) values from each of the separate regressions to obtain SSE(F), the error sum of squares for the full model which allows separate slope and intercept parameters for each data set. Then fit a single regression to the combined data from all data sets to obtain SSE(R), error sum of squares for the reduced model which contains a single set of coefficients a and b (and c for quadratic models) which apply to all data sets. The F statistic for testing the equality of the k regressions is

$$F = \frac{SSE(R) - SSE(F)}{2(k - 1)} \div \frac{SSE(F)}{n - 2k}$$

for simple linear models, and

$$F = \frac{SSE(R) - SSE(F)}{3(k - 1)} \div \frac{SSE(F)}{n - 3k}$$

for quadratic models, where n denotes total number of observations in all k data sets combined. In the linear case, if F is greater than the 95th percentile of the F distribution with 2(k - 1) numerator degrees of freedom and n - 2k denominator degrees of freedom (from Table 9.6.4.9), the hypothesis that the regressions are equal is rejected. In the quadratic case, if F is greater than the 95th percentile of the F distribution with 3(k - 1) numerator degrees of freedom, and n - 3k denominator degrees of freedom, the hypothesis that the regressions are equal is rejected. See Reference 9.6.3.3 for more detail.

9.6.3.5 ***Example of Computations*** — In this example, x represents thickness and y represents the TYS values determined from a group of tensile tests. Values of x and y are as follows:

X	Y
0.100	121
0.100	119
0.200	114
0.200	108
0.300	112
0.300	108
0.400	112
0.400	106
0.500	101
0.500	99

From these data, the following quantities may be calculated:

n	= 10	$(\Sigma x)^2$	= 9
Σx	= 3	$(\Sigma y)^2$	= 121000
Σy	= 1100.0	$(\Sigma x)(\Sigma y)$	= 3300
Σx^2	= 1.1	S_{xx}	= 0.20
Σy^2	= 121452	S_{xy}	= -8.4
Σxy	= 321.6	S_{yy}	= 452.

The slope of the regression line is:

$$b = \frac{S_{xy}}{S_{xx}} = \frac{-8.4}{0.20} = -42 \quad .$$

The y-intercept of the regression line is:

$$a = \frac{\Sigma y - b\Sigma x}{n} = \frac{1100}{10} - \frac{(-42)(3)}{10} = 110 + 12.6 = 122.6 \quad .$$

Thus the final equation of the least squares regression line is:

$$\hat{y} = a + b\,x = 122.6 - 42x \quad .$$

The total of the y data at each x level is needed to calculate lack of fit and pure error sums of squares. These totals are as follows:

x_i	T_i
0.1	240
0.2	222
0.3	220
0.4	218
0.5	200

There are data values at k = 5 different x levels, with $n_i = 2$ values at each level and

$$\sum_{i=1}^{k} (T_i^2/n_i) = \frac{(240)^2}{2} + \ldots + \frac{(200)^2}{2} = 121404 \quad .$$

Thus,

$$SSLF = 121404 - (1100)^2/10 - 352.8 = 51.2$$

and

$$SSPE = 99.2 - 51.2 = 48.$$

The mean square values are computed by dividing corresponding sums of squares by their degrees of freedom. The F_1 and F_2 statistics are then calculated as ratios of mean squares. The analysis of variance table is shown below.

Source of Variation	Degree of Freedom, DF	Sum of Square, SS	Mean Squares, MS	F_{calc}
Regression	1	352.8	352.8	$F_1 = 28.5$
Error	8	99.2	12.4	
Lack of Fit	3	51.2	17.07	$F_2 = 1.78$
Pure Error	5	48.0	9.6	
Total	9	452.0		

Using this equation, the following values of $\hat{y}$ may be computed for the values of x listed previously.

x	$\hat{y}$
0.100	118.4
0.200	114.2
0.300	110.0
0.400	105.8
0.500	101.6

The root mean square error is computed as follows:

$$S_y = \sqrt{\frac{\sum (y - \hat{y})^2}{n - 2}} = \sqrt{\frac{99.2}{8}}$$

or

$$S_y = \sqrt{\frac{S_{yy} - b^2 S_{xx}}{n - 2}} = \sqrt{\frac{452 - (-42)^2(0.2)}{8}} = 3.52 \quad .$$

R^2 is computed as follows:

$$R^2 = \frac{b^2 S_{xx}}{S_{yy}} = \frac{(-42)^2(0.2)}{452} = 0.78$$

Thus, 78 percent of the variability in the y data about its average is explained by the linear relationship between y and x.

The sum of squares for the regression, total and error lines are computed as follows:

$$SSR = (-42)^2\,(0.20) = 352.8$$
$$SST = 452$$
$$SSE = 452 - 352.8 = 99.2.$$

The F_2 value of 1.78 with k - 2 = 3 and n - k = 5 degrees of freedom is less than the value of 5.41 from Table 9.6.4.9 corresponding to 3 numerator and 5 denominator degrees of freedom. This indicates that lack of fit can be considered insignificant. Thus, it is reasonable to assume that a linear regression adequately describes the data. The F_1 value of 28.5 with 1 and n - 2 = 8 degrees of freedom is greater than the value of 5.32 from Table 9.6.4.9 corresponding to 1 numerator and 8 denominator degrees of freedom, so the slope of the regression is found to be significantly different from zero.

9.6.4 TABLES — In this section a number of tables of statistical values that are required for analyses described in the Guidelines are presented. For tables containing various fractiles or confidence levels, only applicable portions are reproduced herein. Table 9.6.4.1 was reproduced by permission from Reference 9.6.4.1. Table 9.6.4.2 was computed specifically for MIL-HDBK-5. Tables 9.6.4.3 through 9.6.4.7 and Table 9.6.4.9 were reproduced or adapted from tables in Reference 9.6, with the addition of a few individual values from various sources. Tables 9.6.4.8 and 9.6.4.10 were computed specifically for MIL-HDBK-5.

Table 9.6.4.1. One-Sided Tolerance Limit Factors[a], k, for the Normal Distribution, 0.95 Confidence, and n-1 Degrees of Freedom

Note: use values for P = 0.99 to determine T_{99}
use values for P = 0.90 to determine T_{90}

n	P = 0.90	P = 0.99	n	P = 0.90	P = 0.99
			31	1.767	3.048
2	20.581	37.094	32	1.758	3.034
3	6.155	10.553	33	1.749	3.020
4	4.162	7.042	34	1.740	3.007
5	3.407	5.741	35	1.732	2.995
6	3.006	5.062	36	1.725	2.983
7	2.755	4.642	37	1.717	2.972
8	2.582	4.354	38	1.710	2.961
9	2.454	4.143	39	1.704	2.951
10	2.355	3.981	40	1.697	2.941
11	2.275	3.852	41	1.691	2.932
12	2.210	3.747	42	1.685	2.923
13	2.155	3.659	43	1.680	2.914
14	2.109	3.585	44	1.674	2.906
15	2.068	3.520	45	1.669	2.898
16	2.033	3.464	46	1.664	2.890
17	2.002	3.414	47	1.659	2.883
18	1.974	3.370	48	1.654	2.876
19	1.949	3.331	49	1.650	2.869
20	1.926	3.295	50	1.646	2.862
21	1.905	3.263	51	1.641	2.856
22	1.886	3.233	52	1.637	2.850
23	1.869	3.206	53	1.633	2.844
24	1.853	3.181	54	1.630	2.838
25	1.838	3.158	55	1.626	2.833
26	1.824	3.136	56	1.622	2.827
27	1.811	3.116	57	1.619	2.822
28	1.799	3.098	58	1.615	2.817
29	1.788	3.080	59	1.612	2.812
30	1.777	3.064	60	1.609	2.807

Table 9.6.4.2. Ranks, r, of Observations, n, for an Unknown Distribution Having the Probability and Confidence of T_{99} and T_{90} Values

T_{99} Value						T_{90} Value					
n	r_{99}	n	r_{99}	n	r_{99}	n	r_{90}	n	r_{90}	n	r_{90}
#298	a	4635	36	8643	72	#28	b	638	52	2693	340
299	1	4749	37	8753	73	29	1	660	54	3797	350
473	2	4862	38	8862	74	46	2	682	56	3901	360
628	3	4975	39	8972	75	61	3	704	58	4005	370
773	4	5088	40	9081	76	76	4	726	60	4109	380
913	5	5201	41	9190	77	89	5	781	65	4213	390
1049	6	5314	42	9300	78	103	6	836	70	4317	400
1182	7	5427	43	9409	79	116	7	890	75	4421	410
1312	8	5539	44	9518	80	129	8	945	80	4525	420
1441	9	5651	45	9627	81	142	9	999	85	4629	430
1568	10	5764	46	9736	82	154	10	1053	90	4733	440
1693	11	5876	47	9845	83	167	11	1107	95	4836	450
1818	12	5988	48	9954	84	179	12	1161	100	4940	460
1941	13	6099	49	10063	85	191	13	1269	110	5044	470
2064	14	6211	50	10172	86	203	14	1376	120	5147	480
2185	15	6323	51	10281	87	215	15	1483	130	5251	490
2305	16	6434	52	10390	88	227	16	1590	140	5354	500
2425	17	6545	53	10498	89	239	17	1696	150	5613	525
2546	18	6657	54	10607	90	251	18	1803	160	5871	550
2665	19	6768	55	10716	91	263	19	1909	170	6130	575
2784	20	6879	56	10824	92	275	20	2015	180	6388	600
2902	21	6990	57	10933	93	298	22	2120	190	6645	625
3020	22	7100	58	11041	94	321	24	2226	200	6903	650
3137	23	7211	59	11150	95	345	26	2331	210	7161	675
3254	24	7322	60	11258	96	368	28	2437	220	7418	700
3371	25	7432	61	11366	97	391	30	2542	230	7727	730
3487	26	7543	62	11475	98	413	32	2647	240	8036	760
3603	27	7653	63	11583	99	436	34	2752	250	8344	790
3719	28	7763	64	11691	100	459	36	2857	260	8652	820
3834	29	7874	65			481	38	2962	270	8960	850
3949	30	7984	66			504	40	3066	280	9268	880
4064	31	8094	67			526	42	3171	290	9576	910
4179	32	8204	68			549	44	3276	300	9884	940
4293	33	8314	69			571	46	3380	310	10191	970
4407	34	8423	70			593	48	3484	320	10499	1000
4521	35	8533	71			615	50	3589	330		

a T_{99} value is lower than value of lowest observation.
b T_{90} value is lower than value of lowest observation.

The following equations may be used to compute ranks in lieu of using table values or for n values greater than these presented in the table:

$$r_{99}\ '\ n/100\ \&\ 1.645\sqrt{99n/10000}\ \%\ 0.29\ \%\ 19.1/n\ ,\ \text{for}\ n\ \$\ 299$$

rounded to the nearest integer. For n less than 299, the T_{99} value does not exist. This approximation is exact for all but 23 values of n in the range of the table (299 # n # 11691), which is an error rate of about 0.2%. For this small percentage of n values, the approximation gives an r value 1 below the actual r, resulting in a conservative T_{99} value. For T_{90} values, the approximation is

$$r_{90} = n/10 - 1.645\sqrt{9n/100} + 0.23 \text{ , for } n \geq 29$$

rounded to the nearest integer. For n less than 29, the T_{90} value does not exist. The approximation is exact for all but 12 values of n in the range of the table ($29 \leq n \leq 10499$), and errs conservatively by one rank for this small percentage (0.1%).

Table 9.6.4.3. 0.95 Fractiles[a] of the Chi-Squared Distribution Associated with df Degrees of Freedom

df	$\chi^2_{0.95}$	df	$\chi^2_{0.95}$
1	3.84	16	26.30
2	5.99	17	27.59
3	7.81	18	28.87
4	9.49	19	30.14
5	11.07	20	31.41
6	12.59	21	32.67
7	14.07	22	33.92
8	15.51	23	35.17
9	16.92	24	36.42
10	18.31	25	37.65
11	19.68	26	38.88
12	21.03	27	40.11
13	22.36	28	41.34
14	23.68	29	42.56
15	25.00	30	43.77

a The following equation may be used to compute 0.95 fractiles of the Chi-Squared distribution in lieu of using table values:

$$\chi^2_{0.95} = \gamma\left(1 - \frac{2}{9\gamma} + 1.645\sqrt{\frac{2}{9\gamma}}\right)^3 + \frac{9}{100\gamma}$$

where γ is the degrees of freedom (df). This approximation is accurate to within 0.2% of the table values. See Reference 9.6.4.3.

9.6.5 ESTIMATION PROCEDURES FOR THE WEIBULL DISTRIBUTION — This section describes procedures required for modeling data with the three-parameter Weibull distribution. Section 9.6.5.1 describes a method for estimating the threshold parameter, τ. Section 9.6.5.2 describes a method for estimating the shape and scale parameters, β and α, respectively. Both methods permit estimation with upper-tail censored data. For a good exposition of such procedures, see Reference 9.6.1.2(a).

9.6.5.1 Estimating the Weibull Population Threshold — This section describes a method for estimating the threshold of a three-parameter Weibull distribution. The same approach is taken for estimating the threshold, whether the purpose is to test goodness-of-fit (Section 9.6.1.4), or to directly calculate T_{99} or T_{90} values (Section 9.2.8). This method applies to uncensored and upper-tail censored data; however, different columns of Table 9.6.4.10 are used. (References 9.2.8(a) and 9.2.8(b) provide details of this method for uncensored data.)

Let K equal the greatest integer less than or equal to min {4n/15, (1-p)n/3}, where p represents the proportion of the upper tail that is censored (p equals 0, 0.2, or 0.5). Define the function $R(\tau)$ by

$$R(\tau) = \sum_{i=K+1}^{3K-2} L_i(\tau) \Big/ \sum_{i=1}^{3K-2} L_i(\tau)$$

where

$$L_i(\tau) = \frac{1}{D_i}\left[\ln\left(X_{(i+1)}-\tau\right) - \ln\left(X_{(i)}-\tau\right)\right]$$

with

$$D_1 = n \ln\left(1 + \frac{1}{n-1}\right),$$

$$D_2 = \left(\frac{n(n-1)}{2}\right) \ln\left(1+\frac{1}{n(n-2)}\right) \quad ,$$

$$D_3 = \left(\frac{n(n-1)(n-2)}{6}\right) \ln\left(1+\frac{2n - 3}{(n-1)^3\ (n-3)}\right) \quad ,$$

$$D_4 = \left(\frac{n(n-1)(n-2)(n-3)}{24}\right) \ln\left(1+\frac{6n^4 - 48n^3 + 140n^2 - 176n + 81}{n(n-4)\ (n-2)^6}\right) \quad ,$$

and

$$D_i = \ln\left[-\ln\left(1 - \frac{i + 0.5}{n + 0.25}\right)\right] - \ln\left[-\ln\left(1 - \frac{i - 0.5}{n + 0.25}\right)\right]$$

for i=5,6,...,3K-2. Finally, let $\bar{X}$ and S represent the sample mean and sample standard deviation, respectively.

Determine γ using the appropriate column of Table 9.6.4.10. The first set of columns in Table 9.6.4.10 is provided for estimating the threshold, τ_{50}, associated with the Anderson-Darling goodness-of-fit test described in Section 9.6.1.4. The second and third sets of columns are provided for estimating τ_{99} and τ_{90}, which are needed to determine T_{99} and T_{90}, as described in Section 9.2.8. Each set of columns includes a column for uncensored data, 20 percent upper-tail censored data, and 50 percent upper-tail censored data.

The estimated threshold parameter, τ, is the solution to the equation $R(\tau) = \gamma$. The function $R(\tau)$ is a monotonically decreasing continuous function of τ. A simple method for finding the solution is as follows. Start with $L = \min(0, \bar{X} - 100S)$ and $H = 0.999999X_{(1)}$. If $R(L) \leq \gamma$, then set $\tau = L$ or if $R(H) \geq \gamma$ then set $\tau = H$. Otherwise reduce the (L,H) interval by calculating $M = (L+H)/2$ and setting $L = M$ if $R(M) \geq \gamma$ or by setting $H = M$ if $R(M) < \gamma$. If $H - L \leq 2\bar{X}/10^6$, then set $\tau = M$ and stop. Otherwise, reduce the (L,H) interval again.

9.6.5.2 Estimating the Shape and Scale Parameters for the Weibull Distribution — This section describes a method for estimation of the shape and scale parameters of the two-parameter Weibull distribution based on data which may be censored in the upper tail. Estimates of the shape and scale parameters are based on the original data corrected for the estimated threshold, τ. That is, the calculations in this section are performed based on $Z_{(1)}, ..., Z_{(n)}$, where $Z_{(i)} = X_{(i)} - \tau$, with τ estimated as in Section 9.6.5.1. The assumption is made here that if the data are censored, then only the r smallest observations in the sample are observed ($1 \leq r \leq n$), where r is some pre-specified number (often based on a percentage); this is called Type II censoring. Thus, the input to this procedure is a total sample size, n, a censored sample size, r, and the sample remaining after censoring $Z_{(1)}, ..., Z_{(r)}$. Define

$$g(\beta) = \frac{\sum_{i=1}^{r} Z_{(i)}^{\beta} \ln Z_{(i)} + (n-r) Z_{(r)}^{\beta} \ln Z_{(r)}}{\sum_{i=1}^{r} Z_{(i)}^{\beta} + (n-r) Z_{(r)}^{\beta}} - \frac{1}{\beta} - \frac{1}{r} \sum_{i=1}^{r} \ln Z_{(i)}$$

Note: When implementing the equation for $g(\beta)$ in software, it may be necessary to divide each Z term that is raised to the β power by a normalizing factor, C, in order to avoid computational difficulties. The factor, C, can be any type of average calculated from the Z values (e.g., geometric mean of the uncensored Z values). Because the C-factor algebraically cancels out of the equation for $g(\beta)$, its use does not change the meaning of the equation in any way.

The shape parameter estimate, β, is the solution to the equation $g(\beta) = 0$. The function $g(\beta)$ is a monotonically increasing continuous function of β. A simple method for finding the solution is as follows. Let S_y denote the standard deviation of $Y_1, ..., Y_r$ where $Y_i = \ln(Z_i)$ for i=1, ..., r. Calculate $I = 1.28/S_y$ as an initial guess at the solution and calculate g(I). If $g(I) > 0$, then find the smallest positive integer k such that $g(I/2^k) < 0$ and let $L = I/2^k$ and $H = I/2^{k-1}$. If $g(I) < 0$, then find the smallest positive integer k such that $g(2^k I) > 0$ and let $L = 2^{k-1} I$, and $H = 2^k I$. Reduce the (L,H) interval by calculating $M = (L+H)/2$ and setting $L = M$ if $g(M) \leq 0$ and/or by setting $H = M$ if $g(M) \geq 0$. If $H-L \leq 2I/10^6$, then set $\beta = M$ and stop. Otherwise, reduce the (L,H) interval again.

Once β has been determined, the scale parameter estimate is defined by

$$\alpha = \left(\frac{1}{r} \left(\sum_{i=1}^{r} Z_{(i)}^{\beta} + (n-r)\ Z_{(r)}^{\beta} \right) \right)^{\frac{1}{\beta}} .$$

REFERENCES

9.2.7.2(a) Weissberg, A., and Beatty, G. H., "Tables of Tolerance-Limit Factors for Normal Distributors", Battelle Memorial Institute (December 1969).

9.2.7.2(b) Owen, D. B., "Tables of Factors for One-Sided Tolerance Limits for a Normal Distribution", Sandia Corporation (April 1958).

9.2.7.2(c) Owen, D. B., *Handbook of Statistical Tables,* Addison-Wesley (1962).

9.2.7.2(d) Guenther, W. C., *Concepts of Statistical Inference,* McGraw-Hill (1965).

9.2.8(a) Jones, R. A., and Scholz, F. W., "A and B-Allowables for the Three Parameter Weibull Distribution", Boeing Computer Services Company Technical Report No. 10 (October 1983).

9.2.8(b) Jones, R. A., and Scholz, F. W., "Tolerance Limits for the Three Parameter Weibull Distribution", Boeing Computer Service Company Technical Report No. 11 (1983).

9.3.2.4(a) Ramberg, W., and Osgood, W. R., "Description of Stress Strain Curves by Three Parameters", National Advisory Committee for Aeronautics, Technical Note 902 (July 1943).

9.3.2.4(b) Hill, H. N., "Determination of Stress-Strain Relations from Offset Yield Strength Values", National Advisory Committee for Aeronautics, Technical Note 927 (February 1944).

9.3.3 Burt, C. W., et al., "Mechanical Properties of Aerospace Structural Alloys Under Biaxial-Stress Conditions", AFML-TR-66-229 (August 1966).

9.3.4.1(a) "Constant-Amplitude Low-Cycle Fatigue Testing", ASTM Standard Recommended Practice E606.

9.3.4.1(b) Landgraf, R. W., "The Resistance of Metals to Cyclic Deformation", Achievement of High Fatigue Resistance in Metals and Alloys, ASTM STP 467, 1970, pp. 3-36.

9.3.4.5(a) "Manual on Statistical Planning and Analysis for Fatigue Experiments", ASTM STP 588 (1975).

9.3.4.5(b) "Statistical Analysis of Linear or Linearized Stress Life (S-N) and Strain Life (ϵ-N) Data", ASTM Standard Practice E739.

9.3.4.5(c) ASTM Special Technical Publication No. 91-A, "A Guide for Fatigue Testing and the Statistical Analysis of Fatigue Data", Supplement to Manual on Fatigue Testing, STP No. 91 (1963).

Journal of Materials, JMLSA, Vol. 4, No. 1, March 1969, pp. 176-188.

9.3.4.8 Sjodahl, L. H., "Extensions of the Multiple Heat Regression Technique Using Centered Data for Individual Heats", Progress in Analysis of Fatigue and Stress Rupture (Data), MPC-Vol. 23, 1984, pp. 47-86.

9.3.4.9(a) Walker, E. K, "The Effect of Stress Ratio During Crack Propagation and Fatigue for 2024-T3 and 7075-T6 Aluminum", Effect of Environment and Complex Load History on Fatigue Life, ASTM STP 462 (1970) pp. 1-14.

9.3.4.9(b) Stulen, F. L., "Fatigue Life Data Displayed by a Single Quantity Relating Alternating and Mean Stresses", AFML-TR-65-121 (1965).

9.3.4.9(c) Topper, T. H., and Sandor, B. I., "Effects of Mean Stress and Prestrain on Fatigue-Damage Summation", Effects of Environment and Complex Load History on Fatigue Life, ASTM STP 462, 1970, pp. 93-104.

9.3.4.11 Snedecor, G. W., and Cochran, W. G., *Statistical Methods*, Seventh Edition, The Iowa State University Press, Ames, Iowa (1980), pp. 115-116.

9.3.4.12 Montgomery, D. C., and Peck, E. A., *Introduction to Linear Regression Analysis*, Wiley, New York (1982).

9.3.4.13 Winer, B. J., *Statistic Principles in Experimental Design*, 2nd Ed., McGraw-Hill, New York (1971).

9.3.4.14(a) Kalbfleisch, J. D., and Prentice, R. L., *The Statistical Analysis of Failure Time Data*, Wiley, New York (1982).

9.3.4.14(b) SAS *Users Guide: Statistical Version 5 ed*., Cary, N.C.: SAS Institute, Inc. (1985).

9.3.6.3 Mandel, J., and Paule, R., "Interlaboratory Evaluation of a Material With Unequal Numbers of Replicates", *Analytical Chemistry*, Vol. 42, No. 11, pp. 1194-1197 (September 1979), correction in Vol. 43, No. 10 (August 1971).

9.3.6.5 "Characterization of Materials for Service at Elevated Temperatures", Report No. MPC-7, Presented at 1978 ASME/CSME Montreal Pressure Vessel and Piping Conference, Montreal, Quebec, Canada (June 25-29, 1978).

9.4.1.3.1(a) "National Aerospace Standard, Fastener Test Method, Method 4, Lap Joint Shear", NASM1312-4.

9.4.1.3.1(b) "National Aerospace Standard, Fastener Test Method, Method 13, Double Shear Test", NASM312-13.

9.4.1.3.1(c) "National Aerospace Standard, Fastener Test Method, Method 20, Single Shear", NASM1312-20.

9.4.2.1 Hood, D., et al., "An Investigation of the Generation and Utilization of Engineering Data on Weldments", AFML-TR-68-268 (October 1968).

by the theory of elasticity (or by experimental procedures that give equivalent values). NOTE—The theory of plasticity should not be used to determine K_t.

Tolerance Interval.—An interval computed so that it will include at least a stated percentage of the population with a stated probability.

Tolerance Level.—The stated probability that the tolerance interval includes at least the stated percentage of the population. It is not the same as a confidence level, but the term confidence level is frequently associated with tolerance intervals.

Tolerance Limits.—The two statistics that define a tolerance interval. (One value may be "minus infinity" or "plus infinity".)

Total Plastic Strain.—Total plastic strain at a specified time is equal to the sum of plastic strain during loading plus creep.

Total Strain.—Total strain at any given time, including initial loading strain (which may include plastic strain in addition to elastic strain) and creep strain, but not including thermal expansion.

Transition Fatigue Life.*—The point on a strain-life diagram where the elastic and plastic strains are equal.

Transverse Direction.—Perpendicular to the principal direction of flow in a worked metal; may be defined as T, LT or ST.

Typical Basis.—A typical property value is an average value and has no statistical assurance associated with it.

Waveform.—The shape of the peak-to-peak variation of a controlled mechanical test variable (for example, load, strain, displacement) as a function of time.

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* Different from ASTM.

A.4 Conversion of U.S. Units of Measure Used in MIL-HDBK-5 to SI Units

Quantity or Property	To Convert From U. S. Unit	Multiply by[a]	SI Unit[b]
Area	in.^{2}	645.16[c]	Millimeter^2 (mm^2)
Force	lb	4.4482	Newton (N)
Length	in.	25.4[c]	Millimeter (mm)
Stress	ksi	6.895	Megapascal (MPa)[d]
Stress intensity factor	ksi $\sqrt{\text{in.}}$	1.0989	Megapascal $\sqrt{\text{meter}}$ (MPa · m$^{1/2}$)[d]
Modulus	10^3 ksi	6.895	Gigapascal (GPa)[d]
Temperature	°F	$\frac{F + 459.67}{1.8}$	Kelvin (K)
Density (ω)	lb/in.^{3}	27.680	Megagram/meter^3 (Mg/m^3)
Specific heat (C)	Btu/lb·F (or Btu·lb^{-1}·F^{-1})	4.1868[c]	Joule/(gram·Kelvin) (J/g·K) or (J·g^{-1} ·K^{-1})
Thermal conductivity (K)	Btu/[(hr)(ft^2)(F)/ft] (or Btu·hr^{-1}·ft^{-2}·F^{-1}·ft)	1.7307	Watt/(meter·Kelvin) W/(m·K) or (W·m^{-1}·K^{-1})
Thermal expansion (α)	in./in./F (or in.·in.$^{-1}$·F^{-1})	1.8	Meter/meter/Kelvin m/(m·K) or (m·m^{-1}·K^{-1})

a Conversion factors to give significant figures are as specified in ASTM E 380, NASA SP-7012, second revision. NBS Special Publication 330, and *Metals Engineering Quarterly.* Note: Multiple conversions between U.S. and SI units should be avoided because significant round-off errors may result.

b

Prefix	Multiple	Prefix	Multiple
giga (G)	10^9	milli (m)	10^{-3}
mega (M)	10^6	micro (μ)	10^{-6}
kilo (k)	10^3		

c Conversion factor is exact.

d One Pascal (Pa) = one Newton/meter^2.

APPENDIX B

B.0 Alloy Index

Alloy Name	Form	Specification	Section
250	Bar	AMS 6512	2.5.1
250	Sheet and Plate	AMS 6520	2.5.1
354.0	Casting	AMS-A-21180	3.9.1
355.0	Permanent Mold Casting	AMS 4281	3.9.2
356.0	Sand Casting	AMS 4217	3.9.4
356.0	Investment Casting	AMS 4260	3.9.4
356.0	Permanent Mold Casting	AMS 4284	3.9.4
359.0	Casting	AMS-A-21180	3.9.8
2014	Bare Sheet and Plate	AMS 4028	3.2.1
2014	Bare Sheet and Plate	AMS 4029	3.2.1
2014	Bar and Rod, Rolled or Cold Finished	AMS 4121	3.2.1
2014	Forging	AMS 4133	3.2.1
2014	Extrusion	AMS 4153	3.2.1
2014	Forging	AMS-A-22771	3.2.1
2014	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/2	3.2.1
2014	Rolled or Drawn Bar, Rod and Shapes	AMS-QQ-A-225/4	3.2.1
2014	Clad Sheet and Plate	AMS-QQ-A-250/3	3.2.1
2014	Forging	AMS-QQ-A-367	3.2.1
2017	Bar and Rod, Rolled or Cold-Finished	AMS 4118	3.2.2
2017	Rolled Bar and Rod	AMS-QQ-A-225/5	3.2.2
2024	Bare Sheet and Plate	AMS 4035	3.2.3
2024	Bare Sheet and Plate	AMS 4037	3.2.3
2024	Tubing, Hydraulic, Seamless, Drawn	AMS 4086	3.2.3
2024	Bar and Rod, Rolled or Cold-Finished	AMS 4120	3.2.3
2024	Extrusion	AMS 4152	3.2.3
2024	Extrusion	AMS 4164	3.2.3
2024	Extrusion	AMS 4165	3.2.3
2024	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/3	3.2.3
2024	Rolled or Drawn Bar, Rod and Wire	AMS-QQ-A-225/6	3.2.3
2024	Bare Sheet and Plate	AMS-QQ-A-250/4	3.2.3
2024	Clad Sheet and Plate	AMS-QQ-A-250/5	3.2.3
2024	Tubing	AMS-WW-T-700/3	3.2.3
2025	Die Forging	AMS 4130	3.2.4
2090	Sheet	AMS 4251	3.2.5
2124	Plate	AMS 4101	3.2.6
2124	Plate	AMS-QQ-A-250/29	3.2.6
2219	Sheet and Plate	AMS 4031	3.2.7
2219	Hand Forging	AMS 4144	3.2.7
2219	Extrusion	AMS 4162	3.2.7
2219	Extrusion	AMS 4163	3.2.7
2219	Sheet and Plate	AMS-QQ-A-250/30	3.2.7
2424	Sheet (Clad)	AMS 4270	3.2.8
2424	Sheet (Bare)	AMS 4273	3.2.8
2519	Plate	MIL-A-46192	3.2.9

Supersedes page B-1 of MIL-HDBK-5H

Key: Underline indicates inactive for new design.

Alloy Name	Form	Specification	Section
2524	Sheet and Plate	AMS 4296	3.2.10
2618	Die and Hand Forgings	AMS 4132	3.2.11
2618	Die Forging	AMS-A-22771	3.2.11
2618	Forging	AMS-QQ-A-367	3.2.11
4130	Bar and Forging	AMS 6348	2.3.1
4130	Sheet, Strip and Plate	AMS 6350	2.3.1
4130	Sheet, Strip and Plate	AMS 6351	2.3.1
4130	Tubing	AMS 6361	2.3.1
4130	Tubing	AMS 6362	2.3.1
4130	Bar and Forging	AMS 6370	2.3.1
4130	Tubing	AMS 6371	2.3.1
4130	Tubing	AMS 6373	2.3.1
4130	Tubing	AMS 6374	2.3.1
4130	Bar and Forging	AMS 6528	2.3.1
4130	Sheet, Strip and Plate	AMS-S-18729	2.3.1
4130	Bar and Forging	AMS-S-6758	2.3.1
4130	Tubing	AMS-T-6736	2.3.1
4135	Sheet, Strip and Plate	AMS 6352	2.3.1
4135	Tubing	AMS 6365	2.3.1
4135	Tubing	AMS 6372	2.3.1
4135	Tubing	AMS-T-6735	2.3.1
4140	Bar and Forging	AMS 6349	2.3.1
4140	Tubing	AMS 6381	2.3.1
4140	Bar and Forging	AMS 6382	2.3.1
4140	Sheet, Strip and Plate	AMS 6395	2.3.1
4140	Bar and Forging	AMS 6529	2.3.1
4140	Bar and Forging	MIL-S-5626	2.3.1
4340	Sheet, Strip and Plate	AMS 6359	2.3.1
4340	Bar and Forging	AMS 6414	2.3.1
4340	Tubing	AMS 6414	2.3.1
4340	Bar and Forging	AMS 6415	2.3.1
4340	Tubing	AMS 6415	2.3.1
4340	Sheet, Strip and Plate	AMS 6454	2.3.1
4340	Bar and Forging	MIL-S-5000	2.3.1
5052	Sheet and Plate	AMS 4015	3.5.1
5052	Sheet and Plate	AMS 4016	3.5.1
5052	Sheet and Plate	AMS 4017	3.5.1
5052	Sheet and Plate	AMS-QQ-A-250/8	3.5.1
5083	Bare Sheet and Plate	AMS 4056	3.5.2
5083	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/4	3.5.2
5083	Bare Sheet and Plate	AMS-QQ-A-250/6	3.5.2
5086	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/5	3.5.3
5086	Sheet and Plate	AMS-QQ-A-250/7	3.5.3
5454	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/6	3.5.4
5454	Sheet and Plate	AMS-QQ-A-250/10	3.5.4
5456	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/7	3.5.5
5456	Sheet and Plate	AMS-QQ-A-250/9	3.5.5
6061	Sheet and Plate	AMS 4025	3.6.2
6061	Sheet and Plate	AMS 4026	3.6.2
6061	Sheet and Plate	AMS 4027	3.6.2
6061	Tubing Seamless, Drawn	AMS 4080	3.6.2
6061	Tubing Seamless, Drawn	AMS 4082	3.6.2
6061	Bar and Rod, Rolled or Cold Finished	AMS 4115	3.6.2

Supersedes page B-2 of MIL-HDBK-5H

Key: Underline indicates inactive for new design.

Alloy Name	Form	Specification	Section
6061	Bar and Rod, Cold Finished	AMS 4116	3.6.2
6061	Bar and Rod, Rolled or Cold Finished	AMS 4117	3.6.2
6061	Forging	AMS 4127	3.6.2
6061	Extrusion	AMS 4160	3.6.2
6061	Extrusion	AMS 4161	3.6.2
6061	Extrusion	AMS 4172	3.6.2
6061	Hand Forging	AMS 4248	3.6.2
6061	Forging	AMS-A-22771	3.6.2
6061	Pipe	MIL-P-25995	3.6.2
6061	Extruded Rod, Bar Shapes and Tubing	AMS-QQ-A-200/8	3.6.2
6061	Rolled Bar, Rod and Shapes	AMS-QQ-A-225/8	3.6.2
6061	Sheet and Plate	AMS-QQ-A-250/11	3.6.2
6061	Forging	AMS-QQ-A-367	3.6.2
6061	Tubing Seamless, Drawn	AMS-WW-T-700/6	3.6.2
6151	Die Forging	AMS 4125	3.6.3
6151	Forging	AMS-A-22771	3.6.3
7010	Plate	AMS 4204	3.7.1
7010	Plate	AMS 4205	3.7.1
7040	Plate	AMS 4211	3.7.2
7050	Bare Plate	AMS 4050	3.7.4
7050	Die Forging	AMS 4107	3.7.4
7050	Hand Forging	AMS 4108	3.7.4
7050	Bare Plate	AMS 4201	3.7.4
7050	Die Forging	AMS 4333	3.7.4
7050	Extruded Shape	AMS 4340	3.7.4
7050	Extruded Shape	AMS 4341	3.7.4
7050	Extruded Shape	AMS 4342	3.7.4
7050	Forging	AMS-A-22771	3.7.4
7055	Plate	AMS 4206	3.7.5
7055	Extrusion	AMS 4337	3.7.5
7075	Bare Sheet and Plate	AMS 4044	3.7.6
7075	Bare Sheet and Plate	AMS 4045	3.7.6
7075	Clad Sheet and Plate	AMS 4049	3.7.6
7075	Bare Plate	AMS 4078	3.7.6
7075	Bar and Rod, Rolled or Cold Finished	AMS 4122	3.7.6
7075	Bar and Rod, Rolled or Cold Finished	AMS 4123	3.7.6
7075	Bar and Rod, Rolled or Cold Finished	AMS 4124	3.7.6
7075	Forging	AMS 4126	3.7.6
7075	Die Forging	AMS 4141	3.7.6
7075	Forging	AMS 4147	3.7.6
7075	Bar and Rod, Rolled or Cold Finished	AMS 4186	3.7.6
7075	Bar and Rod, Rolled or Cold Finished	AMS 4187	3.7.6
7075	Forging	AMS-A-22771	3.7.6
7075	Extruded Bar, Rod and Shapes	AMS-QQ-A-200/11, 15	3.7.6
7075	Rolled or Drawn Bar and Rod	AMS-QQ-A-225/9	3.7.6
7075	Bare Sheet and Plate	AMS-QQ-A-250/12, 24	3.7.6
7075	Clad Sheet and Plate	AMS-QQ-A-250/13, 25	3.7.6
7075	Forging	AMS-QQ-A-367	3.7.6
7150	Bare Plate	AMS 4252 (T7751)	3.7.7
7150	Bare Plate	AMS 4306 (T6151)	3.7.7
7150	Extrusion	AMS 4307 (T61511)	3.7.7
7150	Extrusion	AMS 4345 (T77511)	3.7.7
7175	Die Forging	AMS 4148 (T66)	3.7.8

Supersedes page B-3 of MIL-HDBK-5H

Key: Underline indicates inactive for new design.

Alloy Name	Form	Specification	Section
7175	Die and Hand Forging	AMS 4149 (T74)	3.7.8
7175	Hand Forging	AMS 4179 (T7452)	3.7.8
7175	Extrusion	AMS 4344 (T73511)	3.7.8
7175	Forging	AMS-A-22771	3.7.8
7249	Hand Forging	AMS 4334	3.7.9
7475	Bare Sheet	AMS 4084 (T61)	3.7.10
7475	Bare Sheet	AMS 4085 (T761)	3.7.10
7475	Bare Plate	AMS 4089 (T7651)	3.7.10
7475	Bare Plate	AMS 4090 (T651)	3.7.10
7475	Clad Sheet	AMS 4100 (T761)	3.7.10
7475	Bare Plate	AMS 4202 (T7351)	3.7.10
7475	Clad Sheet	AMS 4207 (T61)	3.7.10
8630	Bar and Forging	AMS 6280	2.3.1
8630	Tubing	AMS 6281	2.3.1
8630	Sheet, Strip and Plate	MIL-S-18728	2.3.1
8630	Bar and Forging	MIL-S-6050	2.3.1
8735	Tubing	AMS 6282	2.3.1
8735	Bar and Forging	AMS 6320	2.3.1
8735	Sheet, Strip and Plate	AMS 6357	2.3.1
8740	Bar and Forging	AMS 6322	2.3.1
8740	Tubing	AMS 6323	2.3.1
8740	Bar and Forging	AMS 6327	2.3.1
8740	Sheet, Strip and Plate	AMS 6358	2.3.1
8740	Bar and Forging	AMS-S-6049	2.3.1
15-5PH	Investment Casting	AMS 5400	2.6.6
15-5PH	Bar, Forging, Ring and Extrusion (CEVM)	AMS 5659	2.6.6
15-5PH	Sheet, Strip and Plate (CEVM)	AMS 5862	2.6.6
17-4PH	Investment Casting (H1100)	AMS 5342	2.6.8
17-4PH	Investment Casting (H1000)	AMS 5343	2.6.8
17-4PH	Investment Casting (H900)	AMS 5344	2.6.8
17-4PH	Sheet, Strip and Plate	AMS 5604	2.6.8
17-4PH	Bar, Forging and Ring	AMS 5643	2.6.8
17-7PH	Plate, Sheet and Strip	AMS 5528	2.6.9
17-7PH	Plate, Sheet and Strip	MIL-S-25043	2.6.9
2024-T3 ARAMID Fiber Reinforced	Sheet Laminate	AMS 4254	7.5.1
280 (300)	Bar	AMS 6514	2.5.1
280 (300)	Sheet and Plate	AMS 6521	2.5.1
300M (0.42C)	Bar and Forging	AMS 6257	2.3.1
300M (0.42C)	Tubing	AMS 6257	2.3.1
300M (0.42C)	Bar and Forging	AMS 6419	2.3.1
300M (0.42C)	Tubing	AMS 6419	2.3.1
300M (0.4C)	Bar and Forging	AMS 6417	2.3.1
300M (0.4C)	Tubing	AMS 6417	2.3.1
4130 - N	Tubing	AMS 6360	2.3.1
4330V	Bar and Forging	AMS 6411	2.3.1
4330V	Tubing	AMS 6411	2.3.1
4330V	Bar and Forging	AMS 6427	2.3.1
4330V	Tubing	AMS 6427	2.3.1
4335V	Bar and Forging	AMS 6429	2.3.1
4335V	Tubing	AMS 6429	2.3.1
4335V	Bar and Forging	AMS 6430	2.3.1
4335V	Tubing	AMS 6430	2.3.1
4335V	Sheet, Strip and Plate	AMS 6433	2.3.1

Alloy Name	Form	Specification	Section
4335V	Sheet, Strip and Plate	AMS 6435	2.3.1
5Cr-Mo-V	Sheet, Strip and Plate	AMS 6437	2.4.1
5Cr-Mo-V	Bar and Forging (CEVM)	AMS 6487	2.4.1
5Cr-Mo-V	Bar and Forging	AMS 6488	2.4.1
6013-T4	Sheet	AMS 4216	3.6.1
6013-T6	Sheet	AMS 4347	3.6.1
7049/7149	Forging	AMS 4111	3.7.3
7049/7149	Extrusion	AMS 4157	3.7.3
7049/7149	Plate	AMS 4200	3.7.3
7049/7149	Forging	AMS 4320	3.7.3
7049/7149	Extrusion	AMS 4343	3.7.3
7049/7149	Forging	AMS-A-22771	3.7.3
7049/7149	Forging	AMS-QQ-A-367	3.7.3
7475-T761 ARAMID Fiber Reinforced	Sheet Laminate	AMS 4302	7.5.2
9Ni-4Co-0.20C	Sheet, Strip and Plate	AMS 6523	2.4.2
9Ni-4Co-0.20C	Sheet, Strip and Plate	AMS 6524	2.4.3
9Ni-4Co-0.20C	Bar and Forging, Tubing	AMS 6526	2.4.3
A201.0	Casting (T7 Temper)	AMS-A-21180	3.8.1
A-286	Sheet, Strip and Plate	AMS 5525	6.2.1
A-286	Bar, Forging, Tubing and Ring	AMS 5731	6.2.1
A-286	Bar, Forging, Tubing and Ring	AMS 5732	6.2.1
A-286	Bar, Forging and Tubing	AMS 5734	6.2.1
A-286	Bar, Forging and Tubing	AMS 5737	6.2.1
A356.0	Casting	AMS 4218	3.9.5
A356.0	Casting	AMS-A-21180	3.9.5
A357.0	Casting	AMS-A-21180	3.9.6
AerMet 100	Bar and Forging	AMS 6478	2.5.3
AerMet 100	Bar and Forging	AMS 6532	2.5.3
AF1410	Bar and Forging	AMS 6527	2.5.2
AISI 1025	Sheet, Strip, and Plate	AMS 5046	2.2.1
AISI 1025	Bar	ASTM A 108	2.2.1
AISI 1025	Sheet and Strip	AMS-S-7952	2.2.1
AISI 1025	Tubing	AMS 5077	2.2.1
AISI 1025 - N	Seamless Tubing	AMS 5075	2.2.1
AISI 1025 - N	Tubing	AMS 5077	2.2.1
AISI 1025 - N	Tubing	AMS-T-5066	2.2.1
AISI 301	Sheet and Strip	AMS 5517	2.7.1
AISI 301	Sheet and Strip	AMS 5518	2.7.1
AISI 301	Sheet and Strip	AMS 5519	2.7.1
AISI 301	Sheet, Strip and Plate	AMS 5901	2.7.1
AISI 301	Sheet and Strip (175 ksi)	AMS 5902	2.7.1
AISI 302	Sheet, Strip and Plate	AMS 5516	2.7.1
AISI 302	Sheet and Strip (125 ksi)	AMS 5903	2.7.1
AISI 302	Sheet and Strip (150 ksi)	AMS 5904	2.7.1
AISI 302	Sheet and Strip (175 ksi)	AMS 5905	2.7.1
AISI 302	Sheet and Strip (185 ksi)	AMS 5906	2.7.1
AISI 304	Sheet and Strip	AMS 5913	2.7.1
AISI 304	Sheet, Strip and Plate (125 ksi)	AMS 5910	2.7.1
AISI 304	Sheet and Strip (150 ksi)	AMS 5911	2.7.1
AISI 304	Sheet and Strip (175 ksi)	AMS 5912	2.7.1
AISI 304	Sheet and Strip (185 ksi)	AMS 5913	2.7.1
AISI 316	Sheet and Strip	AMS 5924	2.7.1
AISI 316	Sheet, Strip and Plate (125 ksi)	AMS 5907	2.7.1

Alloy Name	Form	Specification	Section
Alloy 188	Sheet and Plate	AMS 5608	6.4.2
Alloy 188	Bar and Forging	AMS 5772	6.4.2
AM100A	Investment Casting	AMS 4455	4.3.1
AM100A	Permanent Mold Casting	AMS 4483	4.3.1
AM100A	Casting	MIL-M-46062	4.3.1
AM-350	Sheet and Strip	AMS 5548	2.6.1
AM-355	Sheet and Strip	AMS 5547	2.6.2
AM-355	Plate	AMS 5549	2.6.2
AM-355	Bar, Forging and Forging Stock	AMS 5743	2.6.2
AZ31B	Sheet and Plate	AMS 4375	4.2.1
AZ31B	Plate	AMS 4376	4.2.1
AZ31B	Sheet and Plate	AMS 4377	4.2.1
AZ31B	Forging	ASTM B 91	4.2.1
AZ31B	Extrusion	ASTM B 107	4.2.1
AZ61A	Extrusion	AMS 4350	4.2.2
AZ61A	Forging	ASTM B 91	4.2.2
AZ91C/AZ91E	Sand Casting	AMS 4437	4.3.2
AZ91C/AZ91E	Sand Casting	AMS 4446	4.3.2
AZ91C/AZ91E	Investment Casting	AMS 4452	4.3.2
AZ91C/AZ91E	Casting	MIL-M-46062	4.3.2
AZ92A	Sand Casting	AMS 4434	4.3.3
AZ92A	Permanent Mold Casting	AMS 4484	4.3.3
AZ92A	Casting	MIL-M-46062	4.3.3
C355.0	Casting	AMS-A-21180	3.9.3
Copper Beryllium	Strip (TB00)	AMS 4530	7.3.2
Copper Beryllium	Strip (TD02)	AMS 4532	7.3.2
Copper Beryllium	Bar and Rod (TF00)	AMS 4533	7.3.2
Copper Beryllium	Bar and Rod (TH04)	AMS 4534	7.3.2
Copper Beryllium	Mechanical tubing (TF00)	AMS 4535	7.3.2
Copper Beryllium	Bar, Rod, Shapes and Forging (TB00)	AMS 4650	7.3.2
Copper Beryllium	Bar and Rod (TD04)	AMS 4651	7.3.2
Copper Beryllium	Sheet (TB00, TD01, TD02, TD04)	ASTM B 194	7.3.2
CP Titanium	Sheet, Strip and Plate	AMS 4900	5.2.1
CP Titanium	Sheet, Strip and Plate	AMS 4901	5.2.1
CP Titanium	Sheet, Strip and Plate	AMS 4902	5.2.1
CP Titanium	Bar	AMS 4921	5.2.1
CP Titanium	Extruded Bars and Shapes	AMS-T-81556	5.2.1
CP Titanium	Sheet, Strip and Plate	AMS-T-9046	5.2.1
CP Titanium	Bar	MIL-T-9047	5.2.1
Custom 450	Bar, Forging, Tubing, Wire and Ring (air melted)	AMS 5763	2.6.3
Custom 450	Bar, Forging, Tubing, Wire and Ring (CEM)	AMS 5773	2.6.3
Custom 455	Tubing (welded)	AMS 5578	2.6.4
Custom 455	Bar and Forging	AMS 5617	2.6.4
D357.0	Sand Composite Casting	AMS 4241	3.9.7
D6AC	Bar and Forging	AMS 6431	2.3.1
D6AC	Tubing	AMS 6431	2.3.1
D6AC	Bar and Forging	AMS 6439	2.3.1
D6AC	Sheet, Strip and Plate	AMS 6439	2.3.1
EZ33A	Sand Casting	AMS 4442	4.3.4
Hastelloy X	Sheet and Plate	AMS 5536	6.3.1
Hastelloy X	Bar and Forging	AMS 5754	6.3.1
Haynes®230®	Plate, Sheet, and Strip	AMS 5878	6.3.9
Haynes®230®	Bar and Forging	AMS 5891	6.3.9

Supersedes page B-6 of MIL-HDBK-5H

Key: Underline indicates inactive for new design.

Alloy Name	Form	Specification	Section
Hy-Tuf	Bar and Forging	AMS 6425	2.3.1
Hy-Tuf	Tubing	AMS 6425	2.3.1
Inconel 718	Investment Casting	AMS 5383	6.3.5
Inconel 718	Tubing; Creep Rupture	AMS 5589	6.3.5
Inconel 718	Tubing; Short-Time	AMS 5590	6.3.5
Inconel 718	Sheet, Strip and Plate; Creep Rupture	AMS 5596	6.3.5
Inconel 718	Sheet, Strip and Plate; Short-Time	AMS 5597	6.3.5
Inconel 718	Bar and Forging; Creep Rupture	AMS 5662	6.3.5
Inconel 718	Bar and Forging; Creep Rupture	AMS 5663	6.3.5
Inconel 718	Bar and Forging; Short-Time	AMS 5664	6.3.5
Inconel Alloy 600	Plate, Sheet and Strip	AMS 5540	6.3.2
Inconel Alloy 600	Tubing, Seamless	AMS 5580	6.3.2
Inconel Alloy 600	Bar and Rod	ASTM B 166	6.3.2
Inconel Alloy 600	Forging	ASTM B 564	6.3.2
Inconel Alloy 625	Sheet, Strip and Plate	AMS 5599	6.3.3
Inconel Alloy 625	Bar, Forging and Ring	AMS 5666	6.3.3
Inconel Alloy 706	Sheet, Strip and Plate	AMS 5605	6.3.4
Inconel Alloy 706	Sheet, Strip and Plate	AMS 5606	6.3.4
Inconel Alloy 706	Bar, Forging and Ring	AMS 5701	6.3.4
Inconel Alloy 706	Bar, Forging and Ring	AMS 5702	6.3.4
Inconel Alloy 706	Bar, Forging and Ring	AMS 5703	6.3.4
Inconel Alloy X-750	Sheet, Strip and Plate; Annealed	AMS 5542	6.3.6
Inconel Alloy X-750	Bar and Forging; Equalized	AMS 5667	6.3.6
L-605	Sheet	AMS 5537	6.4.1
L-605	Bar and Forging	AMS 5759	6.4.1
Manganese Bronzes	Casting	AMS 4860	7.3.1
Manganese Bronzes	Casting	AMS 4862	7.3.1
MP159 Alloy	Bar (solution treated and cold drawn)	AMS 5842	7.4.2
MP159 Alloy	Bar (solution treated, cold drawn and aged)	AMS 5843	7.4.2
MP35N Alloy	Bar (solution treated and cold drawn)	AMS 5844	7.4.1
MP35N Alloy	Bar (solution treated, cold drawn and aged)	AMS 5845	7.4.1
N-155	Sheet	AMS 5532	6.2.2
N-155	Tubing (welded)	AMS 5585	6.2.2
N-155	Bar and Forging	AMS 5768	6.2.2
N-155	Bar and Forging	AMS 5769	6.2.2
PH13-8Mo	Bar, Forging Ring and Extrusion (VIM+CEVM)	AMS 5629	2.6.5
PH15-7Mo	Plate, Sheet and Strip	AMS 5520	2.6.7
QE22A Magnesium	Sand Casting	AMS 4418	4.3.5
QE22A Magnesium	Sand Casting	MIL-M-46062	4.3.5
René 41	Plate, Sheet and Strip	AMS 5545	6.3.7
René 41	Bar and Forging	AMS 5713	6.3.7
René 41 - STA	Bar and Forging	AMS 5712	6.3.7
Standard Grade Beryllium	Sheet and Plate	AMS 7902	7.2.1
Standard Grade Beryllium	Bar, Rod, Tubing and Machined Shapes	AMS 7906	7.2.1
Ti-10V-2Fe-3Al (Ti-10-2-3)	Forging	AMS 4983	5.5.3
Ti-10V-2Fe-3Al (Ti-10-2-3)	Forging	AMS 4984	5.5.3
Ti-10V-2Fe-3Al (Ti-10-2-3)	Forging	AMS 4986	5.5.3
Ti-13V-11Cr-3Al	Sheet, Strip and Plate	AMS-T-9046	5.5.1
Ti-13V-11Cr-3Al	Bar	MIL-T-9047	5.5.1
Ti-15V-3Cr-3Sn-3Al (Ti-15-3-3-3)	Sheet and Strip	AMS 4914	5.5.2
Ti-4.5Al-3V-2Fe-2Mo	Sheet	AMS 4899	5.4.3
Ti-5Al-2.5Sn	Sheet, Strip and Plate	AMS 4910	5.3.1
Ti-5Al-2.5Sn	Bar	AMS 4926	5.3.1

Supersedes page B-7 of MIL-HDBK-5H

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Alloy Name	Form	Specification	Section
Ti-5Al-2.5Sn	Forging	AMS 4966	5.3.1
Ti-5Al-2.5Sn	Extruded Bar and Shapes	AMS-T-81556	5.3.1
Ti-5Al-2.5Sn	Sheet, Strip and Plate	AMS-T-9046	5.3.1
Ti-5Al-2.5Sn	Bar	MIL-T-9047	5.3.1
Ti-6Al-2Sn-4Zr-2Mo	Sheet, Strip and Plate	AMS 4919	5.3.3
Ti-6Al-2Sn-4Zr-2Mo	Bar	AMS 4975	5.3.3
Ti-6Al-2Sn-4Zr-2Mo	Forging	AMS 4976	5.3.3
Ti-6Al-2Sn-4Zr-2Mo	Sheet and Strip	AMS-T-9046	5.3.3
Ti-6Al-4V	Sheet, Strip and Plate	AMS 4911	5.4.1
Ti-6Al-4V	Die Forging	AMS 4920	5.4.1
Ti-6Al-4V	Bar and Die Forging	AMS 4928	5.4.1
Ti-6Al-4V	Extrusion	AMS 4934	5.4.1
Ti-6Al-4V	Extrusion	AMS 4935	5.4.1
Ti-6Al-4V	Casting	AMS 4962	5.4.1
Ti-6Al-4V	Bar	AMS 4967	5.4.1
Ti-6Al-4V	Sheet, Strip and Plate	AMS-T-9046	5.4.1
Ti-6Al-4V	Bar	MIL-T-9047	5.4.1
Ti6Al-6V-2Sn	Sheet, Strip and Plate	AMS 4918	5.4.2
Ti6Al-6V-2Sn	Bar and Forging	AMS 4971	5.4.2
Ti6Al-6V-2Sn	Bar and Forging	AMS 4978	5.4.2
Ti6Al-6V-2Sn	Bar and Forging	AMS 4979	5.4.2
Ti6Al-6V-2Sn	Extruded Bar and Shapes	AMS-T-81556	5.4.2
Ti6Al-6V-2Sn	Sheet, Strip and Plate	AMS-T-9046	5.4.2
Ti-8Al-1Mo-1V	Sheet, Strip and Plate	AMS 4915	5.3.2
Ti-8Al-1Mo-1V	Sheet, Strip and Plate	AMS 4916	5.3.2
Ti-8Al-1Mo-1V	Forging	AMS 4973	5.3.2
Ti-8Al-1Mo-1V	Sheet, Strip and Plate	AMS-T-9046	5.3.2
Ti-8Al-1Mo-1V	Bar	MIL-T-9047	5.3.2
Waspaloy	Plate, Sheet and Strip	AMS 5544	6.3.8
Waspaloy	Forging	AMS 5704	6.3.8
Waspaloy	Bar, Forgings and Ring	AMS 5706	6.3.8
Waspaloy	Bar, Forgings and Ring	AMS 5707	6.3.8
Waspaloy	Bar, Forgings and Ring	AMS 5708	6.3.8
Waspaloy	Bar, Forgings and Ring	AMS 5709	6.3.8
ZE41A Magnesium	Sand Casting	AMS 4439	4.3.6
ZK60A-F	Extrusion	ASTM B 107	4.2.3
ZK60A-T5	Extrusion	AMS 4352	4.2.3
ZK60A-T5	Die and Hand Forging	AMS 4362	4.2.3

Supersedes page B-8 of MIL-HDBK-5H

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APPENDIX C

C.0 Specification Index

Specification	Alloy Name	Form/Application	Section
AMS 4015	5052	Sheet and Plate	3.5.1
AMS 4016	5052	Sheet and Plate	3.5.1
AMS 4017	5052	Sheet and Plate	3.5.1
AMS 4025	6061	Sheet and Plate	3.6.2
AMS 4026	6061	Sheet and Plate	3.6.2
AMS 4027	6061	Sheet and Plate	3.6.2
AMS 4028	2014	Bare Sheet and Plate	3.2.1
AMS 4029	2014	Bare Sheet and Plate	3.2.1
AMS 4031	2219	Sheet and Plate	3.2.7
AMS 4035	2024	Bare Sheet and Plate	3.2.3
AMS 4037	2024	Bare Sheet and Plate	3.2.3
AMS 4044	7075	Bare Sheet and Plate	3.7.6
AMS 4045	7075	Bare Sheet and Plate	3.7.6
AMS 4049	7075	Clad Sheet and Plate	3.7.6
AMS 4050	7050	Bare Plate	3.7.4
AMS 4056	5083	Bare Sheet and Plate	3.5.2
AMS 4078	7075	Bare Plate	3.7.6
AMS 4080	6061	Tubing Seamless, Drawn	3.6.2
AMS 4082	6061	Tubing Seamless, Drawn	3.6.2
AMS 4084 (T61)	7475	Bare Sheet	3.7.10
AMS 4085 (T761)	7475	Bare Sheet	3.7.10
AMS 4086	2024	Tubing, Hydraulic, Seamless, Drawn	3.2.3
AMS 4089 (T7651)	7475	Bare Plate	3.7.10
AMS 4090 (T651)	7475	Bare Plate	3.7.10
AMS 4100 (T761)	7475	Clad Sheet	3.7.10
AMS 4101	2124	Plate	3.2.6
AMS 4107	7050	Die Forging	3.7.4
AMS 4108	7050	Hand Forging	3.7.4
AMS 4111	7049/7149	Forging	3.7.3
AMS 4115	6061	Bar and Rod, Rolled or Cold Finished	3.6.2
AMS 4116	6061	Bar and Rod, Cold Finished	3.6.2
AMS 4117	6061	Bar and Rod, Rolled or Cold Finished	3.6.2
AMS 4118	2017	Bar and Rod, Rolled or Cold-Finished	3.2.2
AMS 4120	2024	Bar and Rod, Rolled or Cold-Finished	3.2.3
AMS 4121	2014	Bar and Rod, Rolled or Cold Finished	3.2.1
AMS 4122	7075	Bar and Rod, Rolled or Cold Finished	3.7.6
AMS 4123	7075	Bar and Rod, Rolled or Cold Finished	3.7.6
AMS 4124	7075	Bar and Rod, Rolled or Cold Finished	3.7.6
AMS 4125	6151	Die Forging	3.6.3
AMS 4126	7075	Forging	3.7.6
AMS 4127	6061	Forging	3.6.2
AMS 4130	2025	Die Forging	3.2.4
AMS 4132	2618	Die and Hand Forgings	3.2.11

Supersedes page C-1 of MIL-HDBK-5H

Key: Underline indicates inactive for new design.

Specification	Alloy Name	Form/Application	Section
AMS 4133	2014	Forging	3.2.1
AMS 4141	7075	Die Forging	3.7.6
AMS 4144	2219	Hand Forging	3.2.7
AMS 4147	7075	Forging	3.7.6
AMS 4148 (T66)	7175	Die Forging	3.7.8
AMS 4149 (T74)	7175	Die and Hand Forging	3.7.8
AMS 4152	2024	Extrusion	3.2.3
AMS 4153	2014	Extrusion	3.2.1
AMS 4157	7049/7149	Extrusion	3.7.3
AMS 4160	6061	Extrusion	3.6.2
AMS 4161	6061	Extrusion	3.6.2
AMS 4162	2219	Extrusion	3.2.7
AMS 4163	2219	Extrusion	3.2.7
AMS 4164	2024	Extrusion	3.2.3
AMS 4165	2024	Extrusion	3.2.3
AMS 4172	6061	Extrusion	3.6.2
AMS 4179 (T7452)	7175	Hand Forging	3.7.8
AMS 4186	7075	Bar and Rod, Rolled or Cold Finished	3.7.6
AMS 4187	7075	Bar and Rod, Rolled or Cold Finished	3.7.6
AMS 4200	7049/7149	Plate	3.7.3
AMS 4201	7050	Bare Plate	3.7.4
AMS 4202 (T7351)	7475	Bare Plate	3.7.10
AMS 4204	7010	Plate	3.7.1
AMS 4205	7010	Plate	3.7.1
AMS 4206	7055	Plate	3.7.5
AMS 4207 (T61)	7475	Clad Sheet	3.7.10
AMS 4211	7040	Plate	3.7.2
AMS 4216	6013 (T4)	Sheet	3.6.1
AMS 4217	356.0	Sand Casting	3.9.4
AMS 4218	A356.0	Casting	3.9.5
AMS 4241	D357.0	Sand Composite Casting	3.9.7
AMS 4248	6061	Hand Forging	3.6.2
AMS 4251	2090	Sheet	3.2.5
AMS 4252 (T7751)	7150	Bare Plate	3.7.7
AMS 4254	2024-T3 ARAMID Fiber Reinforced	Sheet Laminate	7.5.1
AMS 4260	356.0	Investment Casting	3.9.4
AMS 4270	2424 (Clad)	Sheet	3.2.8
AMS 4273	2424 (Bare)	Sheet	3.2.8
AMS 4281	355.0	Permanent Mold Casting	3.9.2
AMS 4284	356.0	Permanent Mold Casting	3.9.4
AMS 4296	2524-T3	Sheet and Plate	3.2.10
AMS 4302	7475-T761 ARAMID Fiber Reinforced	Sheet Laminate	7.5.2
AMS 4306 (T6151)	7150	Bare Plate	3.7.7
AMS 4307 (T61511)	7150	Extrusion	3.7.7
AMS 4320	7049/7149	Forging	3.7.3
AMS 4333	7050	Die Forging	3.7.4
AMS 4334	7249	Hand Forging	3.7.9
AMS 4337	7055	Extrusion	3.7.5
AMS 4340	7050	Extruded Shape	3.7.4
AMS 4341	7050	Extruded Shape	3.7.4
AMS 4342	7050	Extruded Shape	3.7.4
AMS 4343	7049/7149	Extrusion	3.7.3

Supersedes page C-2 of MIL-HDBK-5H

Key: <u>Underline indicates inactive for new design.</u>

Specification	Alloy Name	Form/Application	Section
AMS 4344 (T73511)	7175	Extrusion	3.7.8
AMS 4345 (T77511)	7150	Extrusion	3.7.7
AMS 4347	6013 (T6)	Sheet	3.6.1
AMS 4350	AZ61A	Extrusion	4.2.2
AMS 4352	ZK60A-T5	Extrusion	4.2.3
AMS 4362	ZK60A-T5	Die and Hand Forging	4.2.3
AMS 4375	AZ31B	Sheet and Plate	4.2.1
AMS 4376	AZ31B	Plate	4.2.1
AMS 4377	AZ31B	Sheet and Plate	4.2.1
AMS 4418	QE22A Magnesium	Sand Casting	4.3.5
AMS 4434	AZ92A	Sand Casting	4.3.3
AMS 4437	AZ91C/AZ91E	Sand Casting	4.3.2
AMS 4439	ZE41A Magnesium	Sand Casting	4.3.6
AMS 4442	EZ33A	Sand Casting	4.3.4
AMS 4446	AZ91C/AZ91E	Sand Casting	4.3.2
AMS 4452	AZ91C/AZ91E	Investment Casting	4.3.2
AMS 4455	AM100A	Investment Casting	4.3.1
AMS 4483	AM100A	Permanent Mold Casting	4.3.1
AMS 4484	AZ92A	Permanent Mold Casting	4.3.3
AMS 4530	Copper Beryllium	Strip (TB00)	7.3.2
AMS 4532	Copper Beryllium	Strip (TD02)	7.3.2
AMS 4533	Copper Beryllium	Bar and Rod (TF00)	7.3.2
AMS 4534	Copper Beryllium	Bar and Rod (TH04)	7.3.2
AMS 4535	Copper Beryllium	Mechanical tubing (TF00)	7.3.2
AMS 4650	Copper Beryllium	Bar, Rod, Shapes and Forging (TB00)	7.3.2
AMS 4651	Copper Beryllium	Bar and Rod (TD04)	7.3.2
AMS 4860	Manganese Bronzes	Casting	7.3.1
AMS 4862	Manganese Bronzes	Casting	7.3.1
AMS 4899	Ti-4.5Al-3V-2Fe-2Mo	Sheet	5.4.3
AMS 4900	CP Titanium	Sheet, Strip and Plate	5.2.1
AMS 4901	CP Titanium	Sheet, Strip and Plate	5.2.1
AMS 4902	CP Titanium	Sheet, Strip and Plate	5.2.1
AMS 4910	Ti-5Al-2.5Sn	Sheet, Strip and Plate	5.3.1
AMS 4911	Ti-6Al-4V	Sheet, Strip and Plate	5.4.1
AMS 4914	Ti-15V-3Cr-3Sn-3Al (Ti-15-3)-3-3	Sheet and Strip	5.5.2
AMS 4915	Ti-8Al-1Mo-1V	Sheet, Strip and Plate	5.3.2
AMS 4916	Ti-8Al-1Mo-1V	Sheet, Strip and Plate	5.3.2
AMS 4918	Ti6Al-6V-2Sn	Sheet, Strip and Plate	5.4.2
AMS 4919	Ti-6Al-2Sn-4Zr-2Mo	Sheet, Strip and Plate	5.3.3
AMS 4920	Ti-6Al-4V	Die Forging	5.4.1
AMS 4921	CP Titanium	Bar	5.2.1
AMS 4926	Ti-5Al-2.5Sn	Bar	5.3.1
AMS 4928	Ti-6Al-4V	Bar and Die Forging	5.4.1
AMS 4934	Ti-6Al-4V	Extrusion	5.4.1
AMS 4935	Ti-6Al-4V	Extrusion	5.4.1
AMS 4962	Ti-6Al-4V	Casting	5.4.1
AMS 4966	Ti-5Al-2.5Sn	Forging	5.3.1
AMS 4967	Ti-6Al-4V	Bar	5.4.1
AMS 4971	Ti6Al-6V-2Sn	Bar and Forging	5.4.2
AMS 4973	Ti-8Al-1Mo-1V	Forging	5.3.2
AMS 4975	Ti-6Al-2Sn-4Zr-2Mo	Bar	5.3.3
AMS 4976	Ti-6Al-2Sn-4Zr-2Mo	Forging	5.3.3
AMS 4978	Ti6Al-6V-2Sn	Bar and Forging	5.4.2

Specification	Alloy Name	Form/Application	Section
AMS 4979	Ti6Al-6V-2Sn	Bar and Forging	5.4.2
AMS 4983	Ti-10V-2Fe-3Al (Ti-10-2-3)	Forging	5.5.3
AMS 4984	Ti-10V-2Fe-3Al (Ti-10-2-3)	Forging	5.5.3
AMS 4986	Ti-10V-2Fe-3Al (Ti-10-2-3)	Forging	5.5.3
AMS 5046	AISI 1025	Sheet, Strip, and Plate	2.2.1
AMS 5075	AISI 1025 - N	Seamless Tubing	2.2.1
AMS 5077	AISI 1025 - N	Tubing	2.2.1
AMS 5342	17-4PH	Investment Casting (H1100)	2.6.8
AMS 5343	17-4PH	Investment Casting (H1000)	2.6.8
AMS 5344	17-4PH	Investment Casting (H900)	2.6.8
AMS 5383	Inconel 718	Investment Casting	6.3.5
AMS 5400	15-5PH	Investment Casting	2.6.6
AMS 5513	AISI 301	Sheet, Strip and Plate	2.7.1
AMS 5516	AISI 302	Sheet, Strip and Plate	2.7.1
AMS 5517	AISI 301	Sheet and Strip (125 ksi)	2.7.1
AMS 5518	AISI 301	Sheet and Strip (150 ksi)	2.7.1
AMS 5519	AISI 301	Sheet and Strip (185 ksi)	2.7.1
AMS 5520	PH15-7Mo	Plate, Sheet and Strip	2.6.7
AMS 5524	AISI 316	Sheet, Strip and Plate	2.7.1
AMS 5525	A-286	Sheet, Strip and Plate	6.2.1
AMS 5528	17-7PH	Plate, Sheet and Strip	2.6.9
AMS 5532	N-155	Sheet	6.2.2
AMS 5536	Hastelloy X	Sheet and Plate	6.3.1
AMS 5537	L-605	Sheet	6.4.1
AMS 5540	Inconel Alloy 600	Plate, Sheet and Strip	6.3.2
AMS 5542	Inconel Alloy X-750	Sheet, Strip and Plate; Annealed	6.3.6
AMS 5544	Waspaloy	Plate, Sheet and Strip	6.3.8
AMS 5545	René 41	Plate, Sheet and Strip	6.3.7
AMS 5547	AM-355	Sheet and Strip	2.6.2
AMS 5548	AM-350	Sheet and Strip	2.6.1
AMS 5549	AM-355	Plate	2.6.2
AMS 5578	Custom 455	Tubing (welded)	2.6.4
AMS 5580	Inconel Alloy 600	Tubing, Seamless	6.3.2
AMS 5585	N-155	Tubing (welded)	6.2.2
AMS 5589	Inconel 718	Tubing; Creep Rupture	6.3.5
AMS 5590	Inconel 718	Tubing; Short-Time	6.3.5
AMS 5596	Inconel 718	Sheet, Strip and Plate; Creep Rupture	6.3.5
AMS 5597	Inconel 718	Sheet, Strip and Plate; Short-Time	6.3.5
AMS 5599	Inconel Alloy 625	Sheet, Strip and Plate	6.3.3
AMS 5604	17-4PH	Sheet, Strip and Plate	2.6.8
AMS 5605	Inconel Alloy 706	Sheet, Strip and Plate	6.3.4
AMS 5606	Inconel Alloy 706	Sheet, Strip and Plate	6.3.4
AMS 5608	Alloy 188	Sheet and Plate	6.4.2
AMS 5617	Custom 455	Bar and Forging	2.6.4
AMS 5629	PH13-8Mo	Bar, Forging Ring and Extrusion (VIM+CEVM)	2.6.5
AMS 5643	17-4PH	Bar, Forging and Ring	2.6.8
AMS 5659	15-5PH	Bar, Forging, Ring and Extrusion (CEVM)	2.6.6
AMS 5662	Inconel 718	Bar and Forging; Creep Rupture	6.3.5
AMS 5663	Inconel 718	Bar and Forging; Creep Rupture	6.3.5
AMS 5664	Inconel 718	Bar and Forging; Short-Time	6.3.5
AMS 5666	Inconel Alloy 625	Bar, Forging and Ring	6.3.3
AMS 5667	Inconel Alloy X-750	Bar and Forging; Equalized	6.3.6
AMS 5701	Inconel Alloy 706	Bar, Forging and Ring	6.3.4

Supersedes page C-4 of MIL-HDBK-5H

Key: Underline indicates inactive for new design.

Specification	Alloy Name	Form/Application	Section
AMS 5702	Inconel Alloy 706	Bar, Forging and Ring	6.3.4
AMS 5703	Inconel Alloy 706	Bar, Forging and Ring	6.3.4
AMS 5704	Waspaloy	Forging	6.3.8
AMS 5706	Waspaloy	Bar, Forgings and Ring	6.3.8
AMS 5707	Waspaloy	Bar, Forgings and Ring	6.3.8
AMS 5708	Waspaloy	Bar, Forgings and Ring	6.3.8
AMS 5709	Waspaloy	Bar, Forgings and Ring	6.3.8
AMS 5712	René 41 - STA	Bar and Forging	6.3.7
AMS 5713	René 41	Bar and Forging	6.3.7
AMS 5731	A-286	Bar, Forging, Tubing and Ring	6.2.1
AMS 5732	A-286	Bar, Forging, Tubing and Ring	6.2.1
AMS 5734	A-286	Bar, Forging and Tubing	6.2.1
AMS 5737	A-286	Bar, Forging and Tubing	6.2.1
AMS 5743	AM-355	Bar, Forging and Forging Stock	2.6.2
AMS 5754	Hastelloy X	Bar and Forging	6.3.1
AMS 5759	L-605	Bar and Forging	6.4.1
AMS 5763	Custom 450	Bar, Forging, Tubing, Wire and Ring (air melted)	2.6.3
AMS 5768	N-155	Bar and Forging	6.2.2
AMS 5769	N-155	Bar and Forging	6.2.2
AMS 5772	Alloy 188	Bar and Forging	6.4.2
AMS 5773	Custom 450	Bar, Forging, Tubing, Wire and Ring (CEM)	2.6.3
AMS 5842	MP159 Alloy	Bar (solution treated and cold drawn)	7.4.2
AMS 5843	MP159 Alloy	Bar (solution treated, cold drawn and aged)	7.4.2
AMS 5844	MP35N Alloy	Bar (solution treated and cold drawn)	7.4.1
AMS 5845	MP35N Alloy	Bar (solution treated, cold drawn and aged)	7.4.1
AMS 5862	15-5PH	Sheet, Strip and Plate (CEVM)	2.6.6
AMS 5878	Haynes®230®	Plate, Sheet and Strip	6.3.9
AMS 5891	Haynes®230®	Bar and Forging	6.3.9
AMS 5901	AISI 301	Plate, Sheet and Strip	2.7.1
AMS 5902	AISI 301	Sheet and Strip (175 ksi)	2.7.1
AMS 5903	AISI 302	Sheet and Strip (125 ksi)	2.7.1
AMS 5904	AISI 302	Sheet and Strip (150 ksi)	2.7.1
AMS 5905	AISI 302	Sheet and Strip (175 ksi)	2.7.1
AMS 5906	AISI 302	Sheet and Strip (185 ksi)	2.7.1
AMS 5907	AISI 316	Sheet, Strip and Plate (125 ksi)	2.7.1
AMS 5910	AISI 304	Sheet, Strip and Plate (125 ksi)	2.7.1
AMS 5911	AISI 304	Sheet and Strip (150 ksi)	2.7.1
AMS 5912	AISI 304	Sheet and Strip (175 ksi)	2.7.1
AMS 5913	AISI 304	Sheet and Strip (185 ksi)	2.7.1
AMS 6257	300M (0.42C)	Bar and Forging	2.3.1
AMS 6257	300M (0.42C)	Tubing	2.3.1
AMS 6280	8630	Bar and Forging	2.3.1
AMS 6281	8630	Tubing	2.3.1
AMS 6282	8735	Tubing	2.3.1
AMS 6320	8735	Bar and Forging	2.3.1
AMS 6322	8740	Bar and Forging	2.3.1
AMS 6323	8740	Tubing	2.3.1
AMS 6327	8740	Bar and Forging	2.3.1
AMS 6348	4130	Bar and Forging	2.3.1
AMS 6349	4140	Bar and Forging	2.3.1
AMS 6350	4130	Sheet, Strip and Plate	2.3.1
AMS 6351	4130	Sheet, Strip and Plate	2.3.1
AMS 6352	4135	Sheet, Strip and Plate	2.3.1

Supersedes page C-5 of MIL-HDBK-5H

Key: Underline indicates inactive for new design.

Specification	Alloy Name	Form/Application	Section
AMS 6355	8630	Tubing	2.3.1
AMS 6357	8735	Sheet, Strip and Plate	2.3.1
AMS 6358	8740	Sheet, Strip and Plate	2.3.1
AMS 6359	4340	Sheet, Strip and Plate	2.3.1
AMS 6360	4130	Tubing (normalized)	2.3.1
AMS 6361	4130	Tubing	2.3.1
AMS 6362	4130	Tubing	2.3.1
AMS 6365	4135	Tubing	2.3.1
AMS 6370	4130	Bar and Forging	2.3.1
AMS 6371	4130	Tubing	2.3.1
AMS 6372	4135	Tubing	2.3.1
AMS 6373	4130	Tubing	2.3.1
AMS 6374	4130	Tubing	2.3.1
AMS 6381	4140	Tubing	2.3.1
AMS 6382	4140	Bar and Forging	2.3.1
AMS 6395	4140	Sheet, Strip and Plate	2.3.1
AMS 6411	4330V	Bar and Forging	2.3.1
AMS 6411	4330V	Tubing	2.3.1
AMS 6414	4340	Bar and Forging	2.3.1
AMS 6414	4340	Tubing	2.3.1
AMS 6415	4340	Bar and Forging	2.3.1
AMS 6415	4340	Tubing	2.3.1
AMS 6417	300M (0.4C)	Bar and Forging	2.3.1
AMS 6417	300M (0.4C)	Tubing	2.3.1
AMS 6419	300M (0.42C)	Bar and Forging	2.3.1
AMS 6419	300M (0.42C)	Tubing	2.3.1
AMS 6425	Hy-Tuf	Bar and Forging	2.3.1
AMS 6425	Hy-Tuf	Tubing	2.3.1
AMS 6427	4330V	Bar and Forging	2.3.1
AMS 6427	4330V	Tubing	2.3.1
AMS 6429	4335V	Bar and Forging	2.3.1
AMS 6429	4335V	Tubing	2.3.1
AMS 6430	4335V	Bar and Forging	2.3.1
AMS 6430	4335V	Tubing	2.3.1
AMS 6431	D6AC	Bar and Forging	2.3.1
AMS 6431	D6AC	Tubing	2.3.1
AMS 6433	4335V	Sheet, Strip and Plate	2.3.1
AMS 6435	4335V	Sheet, Strip and Plate	2.3.1
AMS 6437	5Cr-Mo-V	Sheet, Strip and Plate	2.4.1
AMS 6439	D6AC	Sheet, Strip and Plate	2.3.1
AMS 6439	D6AC	Bar and Forging	2.3.1
AMS 6454	4340	Sheet, Strip and Plate	2.3.1
AMS 6478	AerMet 100	Bar and Forging	2.5.3
AMS 6487	5Cr-Mo-V	Bar and Forging (CEVM)	2.4.1
AMS 6488	5Cr-Mo-V	Bar and Forging	2.4.1
AMS 6512	250	Bar	2.5.1
AMS 6514	280 (300)	Bar	2.5.1
AMS 6520	250	Sheet and Plate	2.5.1
AMS 6521	280 (300)	Sheet and Plate	2.5.1
AMS 6523	9Ni-4Co-0.20C	Sheet, Strip and Plate	2.4.2
AMS 6524	9Ni-4Co-0.20C	Sheet, Strip and Plate	2.4.3
AMS 6526	9Ni-4Co-0.20C	Bar and Forging, Tubing	2.4.3
AMS 6527	AF1410	Bar and Forging	2.5.2

Supersedes page C-6 of MIL-HDBK-5H

Key: Underline indicates inactive for new design.

Specification	Alloy Name	Form/Application	Section
AMS 6528	4130	Bar and Forging	2.3.1
AMS 6529	4140	Bar and Forging	2.3.1
AMS 6532	AerMet 100	Bar and Forging	2.5.3
AMS 7902	Standard Grade Beryllium	Sheet and Plate	7.2.1
AMS 7906	Standard Grade Beryllium	Bar, Rod, Tubing and Machined Shapes	7.2.1
AMS-A-21180	A201.0	Casting (T7 Temper)	3.8.1
AMS-A-21180	354.0	Casting	3.9.1
AMS-A-21180	C355.0	Casting	3.9.3
AMS-A-21180	A356.0	Casting	3.9.5
AMS-A-21180	A357.0	Casting	3.9.6
AMS-A-21180	359.0	Casting	3.9.8
AMS-A-22771	2014	Forging	3.2.1
AMS-A-22771	2618	Die Forging	3.2.11
AMS-A-22771	6061	Forging	3.6.2
AMS-A-22771	6151	Forging	3.6.3
AMS-A-22771	7049/7149	Forging	3.7.3
AMS-A-22771	7050	Forging	3.7.4
AMS-A-22771	7075	Forging	3.7.6
AMS-A-22771	7175	Forging	3.7.8
AMS-QQ-A-367	2014	Forging	3.2.1
AMS-QQ-A-367	2618	Forging	3.2.11
AMS-QQ-A-367	6061	Forging	3.6.2
AMS-QQ-A-367	7049/7149	Forging	3.7.3
AMS-QQ-A-367	7075	Forging	3.7.6
AMS-QQ-A-200/2	2014	Extruded Bar, Rod and Shapes	3.2.1
AMS-QQ-A-200/3	2024	Extruded Bar, Rod and Shapes	3.2.3
AMS-QQ-A-200/4	5083	Extruded Bar, Rod and Shapes	3.5.2
AMS-QQ-A-200/5	5086	Extruded Bar, Rod and Shapes	3.5.3
AMS-QQ-A-200/6	5454	Extruded Bar, Rod and Shapes	3.5.4
AMS-QQ-A-200/7	5456	Extruded Bar, Rod and Shapes	3.5.5
AMS-QQ-A-200/8	6061	Extruded Rod, Bar Shapes and Tubing	3.6.2
AMS-QQ-A-200/11, 15	7075	Extruded Bar, Rod and Shapes	3.7.6
AMS-QQ-A-225/4	2014	Rolled or Drawn Bar, Rod and Shapes	3.2.1
AMS-QQ-A-225/5	2017	Rolled Bar and Rod	3.2.2
AMS-QQ-A-225/6	2024	Rolled or Drawn Bar, Rod and Wire	3.2.3
AMS-QQ-A-225/8	6061	Rolled Bar, Rod and Shapes	3.6.2
AMS-QQ-A-225/9	7075	Rolled or Drawn Bar and Rod	3.7.6
AMS-QQ-A-250/3	2014	Clad Sheet and Plate	3.2.1
AMS-QQ-A-250/4	2024	Bare Sheet and Plate	3.2.3
AMS-QQ-A-250/5	2024	Clad Sheet and Plate	3.2.3
AMS-QQ-A-250/6	5083	Bare Sheet and Plate	3.5.2
AMS-QQ-A-250/7	5086	Sheet and Plate	3.5.3
AMS-QQ-A-250/8	5052	Sheet and Plate	3.5.1
AMS-QQ-A-250/9	5456	Sheet and Plate	3.5.5
AMS-QQ-A-250/10	5454	Sheet and Plate	3.5.4
AMS-QQ-A-250/11	6061	Sheet and Plate	3.6.2
AMS-QQ-A-250/12, 24	7075	Bare Sheet and Plate	3.7.6
AMS-QQ-A-250/13, 25	7075	Clad Sheet and Plate	3.7.6
AMS-QQ-A-250/29	2124	Plate	3.2.6
AMS-QQ-A-250/30	2219	Sheet and Plate	3.2.7
AMS-S-5000	4340	Bar and Forging	2.3.1
AMS-S-5626	4140	Bar and Forging	2.3.1
AMS-S-6049	8740	Bar and Forging	2.3.1

Supersedes page C-7 of MIL-HDBK-5H

Key: Underline indicates inactive for new design.

Specification	Alloy Name	Form/Application	Section
AMS-S-6050	8630	Bar and Forging	2.3.1
AMS-S-6758	4130	Bar and Forging	2.3.1
AMS-S-7952	AISI 1025	Sheet and Strip	2.2.1
AMS-S-18728	8630	Sheet, Strip and Plate	2.3.1
AMS-S-18729	4130	Sheet, Strip and Plate	2.3.1
AMS-T-5066	AISI 1025 - N	Tubing	2.2.1
AMS-T-6735	4135	Tubing	2.3.1
AMS-T-6736	4130	Tubing	2.3.1
AMS-T-81556	CP Titanium	Extruded Bars and Shapes	5.2.1
AMS-T-81556	Ti-5Al-2.5Sn	Extruded Bar and Shapes	5.3.1
AMS-T-81556	Ti6Al-6V-2Sn	Extruded Bar and Shapes	5.4.2
AMS-T-9046	CP Titanium	Sheet, Strip and Plate	5.2.1
AMS-T-9046	Ti-5Al-2.5Sn	Sheet, Strip and Plate	5.3.1
AMS-T-9046	Ti-8Al-1Mo-1V	Sheet, Strip and Plate	5.3.2
AMS-T-9046	Ti-6Al-2Sn-4Zr-2Mo	Sheet and Strip	5.3.3
AMS-T-9046	Ti-6Al-4V	Sheet, Strip and Plate	5.4.1
AMS-T-9046	Ti6Al-6V-2Sn	Sheet, Strip and Plate	5.4.2
AMS-T-9046	Ti-13V-11Cr-3Al	Sheet, Strip and Plate	5.5.1
AMS-WW-T-700/3	2024	Tubing	3.2.3
AMS-WW-T-700/6	6061	Tubing Seamless, Drawn	3.6.2
ASTM A 108	AISI 1025	Bar	2.2.1
ASTM B 91	AZ31B	Forging	4.2.1
ASTM B 91	AZ61A	Forging	4.2.2
ASTM B 107	ZK60A-F	Extrusion	4.2.3
ASTM B 107	AZ31B	Extrusion	4.2.1
ASTM B 166	Inconel Alloy 600	Bar and Rod	6.3.2
ASTM B 194	Copper Beryllium	Sheet (TB00, TD01, TD02, TD04)	7.3.2
ASTM B 564	Inconel Alloy 600	Forging	6.3.2
MIL-A-46192	2519	Plate	3.2.9
MIL-M-46062	AM100A	Casting	4.3.1
MIL-M-46062	AZ91C/AZ91E	Casting	4.3.2
MIL-M-46062	AZ92A	Casting	4.3.3
MIL-M-46062	QE22A Magnesium	Sand Casting	4.3.5
MIL-P-25995	6061	Pipe	3.6.2
MIL-S-25043	17-7PH	Plate, Sheet and Strip	2.6.9
MIL-T-9047	CP Titanium	Bar	5.2.1
MIL-T-9047	Ti-5Al-2.5Sn	Bar	5.3.1
MIL-T-9047	Ti-8Al-1Mo-1V	Bar	5.3.2
MIL-T-9047	Ti-6Al-4V	Bar	5.4.1
MIL-T-9047	Ti-13V-11Cr-3Al	Bar	5.5.1

APPENDIX D

D.0 Subject Index

APPENDIX E

E.0 Figure Index

Figure No.	Current Form	Figure No.	Current Form
1.4.4.1	Scanned	2.3.1.3.6(c)	Vector Graphic
1.4.8.2.1(a)	Scanned	2.3.1.3.6(d)	Scanned
1.4.8.2.1(b)	Scanned	2.3.1.3.6(e)	Vector Graphic
1.4.9.3(a)	Scanned	2.3.1.3.6(f)	Vector Graphic
1.4.11.1	Scanned	2.3.1.3.6(g)	Vector Graphic
1.4.11.3	Scanned	2.3.1.3.8(a)	Vector Graphic
1.4.12.2	Scanned	2.3.1.3.8(b)	Vector Graphic
1.4.12.3	Scanned	2.3.1.3.8(c)	Vector Graphic
1.4.12.4	Scanned	2.3.1.3.8(d)	Vector Graphic
1.4.12.4.1	Scanned	2.3.1.3.8(e)	Vector Graphic
1.4.13.2(a)	Scanned	2.3.1.3.8(f)	Vector Graphic
1.4.13.2(b)	Scanned	2.3.1.3.8(g)	Vector Graphic
1.4.13.4	Scanned	2.3.1.3.8(h)	Vector Graphic
1.6.2.2	Scanned	2.3.1.3.8(i)	Vector Graphic
1.6.4.4(a)	Vector Graphic	2.3.1.3.8(j)	Vector Graphic
1.6.4.4(b)	Vector Graphic	2.3.1.3.8(k)	Vector Graphic
1.6.4.4(c)	Vector Graphic	2.3.1.3.8(l)	Vector Graphic
1.6.4.4(d)	Vector Graphic	2.3.1.3.8(m)	Vector Graphic
1.6.4.4(e)	Vector Graphic	2.3.1.3.8(n)	Vector Graphic
1.6.4.4(f)	Vector Graphic	2.3.1.3.8(o)	Vector Graphic
1.6.4.4(g)	Vector Graphic	2.3.1.4.8(a)	Scanned
1.6.4.4(h)	Vector Graphic	2.3.1.4.8(b)	Scanned
1.6.4.4(i)	Vector Graphic	2.3.1.4.8(c)	Scanned
2.2.1.0	Vector Graphic	2.3.1.4.8(d)	Scanned
2.3.0.2	Scanned	2.3.1.4.9	Scanned
2.3.1.0	Vector Graphic	2.3.1.5.9	Scanned
2.3.1.1.1	Vector Graphic	2.4.1.0	Vector Graphic
2.3.1.1.2	Vector Graphic	2.4.1.1.1(a)	Vector Graphic
2.3.1.1.3	Vector Graphic	2.4.1.1.1(b)	Vector Graphic
2.3.1.1.4	Vector Graphic	2.4.1.1.2(a)	Vector Graphic
2.3.1.2.6(a)	Vector Graphic	2.4.1.1.2(b)	Vector Graphic
2.3.1.2.6(b)	Vector Graphic	2.4.1.1.3(a)	Vector Graphic
2.3.1.2.6(c)	Vector Graphic	2.4.1.1.3(b)	Vector Graphic
2.3.1.2.8(a)	Vector Graphic	2.4.1.1.4	Vector Graphic
2.3.1.2.8(b)	Vector Graphic	2.4.2.0	Vector Graphic
2.3.1.2.8(c)	Vector Graphic	2.4.2.1.1	Vector Graphic
2.3.1.2.8(d)	Vector Graphic	2.4.2.1.2	Vector Graphic
2.3.1.2.8(e)	Vector Graphic	2.4.2.1.4	Vector Graphic
2.3.1.2.8(f)	Vector Graphic	2.4.2.1.6(a)	Vector Graphic
2.3.1.2.8(g)	Vector Graphic	2.4.2.1.6(b)	Vector Graphic
2.3.1.2.8(h)	Vector Graphic	2.4.3.0	Vector Graphic
2.3.1.3.6(a)	Vector Graphic	2.4.3.1.1	Vector Graphic
2.3.1.3.6(b)	Vector Graphic	2.4.3.1.2	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
2.4.3.1.3	Vector Graphic	2.6.4.0	Vector Graphic
2.4.3.1.4	Vector Graphic	2.6.4.1.1	Vector Graphic
2.4.3.1.6(a)	Vector Graphic	2.6.4.1.2	Vector Graphic
2.4.3.1.6(b)	Vector Graphic	2.6.4.1.5	Vector Graphic
2.4.3.1.6(c)	Vector Graphic	2.6.4.1.6	Vector Graphic
2.4.3.1.6(d)	Vector Graphic	2.6.4.1.8(a)	Scanned
2.4.3.1.8	Scanned	2.6.4.1.8(b)	Scanned
2.5.0.2(a)	Vector Graphic	2.6.4.2.1	Vector Graphic
2.5.1.0	Vector Graphic	2.6.4.2.2	Vector Graphic
2.5.1.1.1	Vector Graphic	2.6.4.2.5	Scanned
2.5.1.1.2	Vector Graphic	2.6.4.2.6	Vector Graphic
2.5.1.1.3	Vector Graphic	2.6.4.2.8	Scanned
2.5.1.1.4	Vector Graphic	2.6.5.0	Vector Graphic
2.5.1.1.6(a)	Vector Graphic	2.6.5.1.1	Vector Graphic
2.5.1.1.6(b)	Vector Graphic	2.6.5.1.6(a)	Vector Graphic
2.5.1.1.6(c)	Vector Graphic	2.6.5.1.6(b)	Vector Graphic
2.5.1.1.6(d)	Vector Graphic	2.6.5.1.6(c)	Vector Graphic
2.5.1.1.6(e)	Scanned	2.6.5.1.8(a)	Vector Graphic
2.5.2.1.6(a)	Vector Graphic	2.6.5.1.8(b)	Vector Graphic
2.5.2.1.6(b)	Vector Graphic	2.6.5.1.8(c)	Vector Graphic
2.5.3.1.6(a)	Vector Graphic	2.6.6.0	Vector Graphic
2.5.3.1.6(b)	Vector Graphic	2.6.6.1.1	Vector Graphic
2.5.3.1.6(c)	Vector Graphic	2.6.6.1.4	Vector Graphic
2.5.3.2.6(a)	Vector Graphic	2.6.6.1.6(a)	Vector Graphic
2.5.3.2.6(b)	Vector Graphic	2.6.6.1.6(b)	Scanned
2.5.3.2.6(c)	Vector Graphic	2.6.6.1.6(c)	Vector Graphic
2.6.1.0	Vector Graphic	2.6.6.2.2	Vector Graphic
2.6.1.1.1	Vector Graphic	2.6.6.2.6(a)	Scanned
2.6.1.1.2	Vector Graphic	2.6.6.2.6(b)	Vector Graphic
2.6.1.1.3	Vector Graphic	2.6.6.2.8(a)	Vector Graphic
2.6.1.1.4	Vector Graphic	2.6.6.2.8(b)	Vector Graphic
2.6.1.1.6(a)	Vector Graphic	2.6.6.2.8(c)	Vector Graphic
2.6.1.1.6(b)	Vector Graphic	2.6.6.3.2	Scanned
2.6.2.0	Vector Graphic	2.6.6.3.6	Scanned
2.6.2.1.1	Scanned	2.6.7.0	Vector Graphic
2.6.2.1.2	Vector Graphic	2.6.7.1.1	Scanned
2.6.2.1.3	Scanned	2.6.7.1.4	Scanned
2.6.2.1.4	Vector Graphic	2.6.7.1.6(a)	Scanned
2.6.3.0	Vector Graphic	2.6.7.1.6(b)	Scanned
2.6.3.1.1	Vector Graphic	2.6.7.1.6(c)	Scanned
2.6.3.1.2	Vector Graphic	2.6.7.1.8(a)	Scanned
2.6.3.1.5	Vector Graphic	2.6.7.1.8(b)	Scanned
2.6.3.1.6	Vector Graphic	2.6.7.1.8(c)	Scanned
2.6.3.1.8	Scanned	2.6.7.1.8(d)	Scanned
2.6.3.2.1	Vector Graphic	2.6.7.1.8(e)	Vector Graphic
2.6.3.2.2	Vector Graphic	2.6.7.1.8(f)	Scanned
2.6.3.2.5	Vector Graphic	2.6.8.0	Vector Graphic
2.6.3.2.6	Vector Graphic	2.6.8.1.2	Vector Graphic
2.6.3.2.8	Scanned	2.6.8.1.3	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
2.6.8.1.4	Vector Graphic	2.8.3.2(f)	Vector Graphic
2.6.8.1.8(a)	Scanned	2.8.3.2(g)	Scanned
2.6.8.1.8(b)	Scanned	2.8.3.2(h)	Scanned
2.6.8.1.8(c)	Scanned	2.8.3.2(i)	Vector Graphic
2.6.8.2.1	Vector Graphic	2.8.3.2(j)	Scanned
2.6.8.2.6(a)	Vector Graphic	3.1.2.1.1(a)	Scanned
2.6.8.2.6(b)	Vector Graphic	3.1.2.1.1(b)	Scanned
2.6.8.3.6(a)	Vector Graphic	3.1.2.1.1(c)	Scanned
2.6.8.3.6(b)	Vector Graphic	3.2.1.0	Vector Graphic
2.6.8.4.8	Scanned	3.2.1.1.1(a)	Scanned
2.6.8.5.8	Scanned	3.2.1.1.1(b)	Vector Graphic
2.6.8.6.1	Vector Graphic	3.2.1.1.1(c)	Vector Graphic
2.6.9.0	Vector Graphic	3.2.1.1.1(d)	Vector Graphic
2.6.9.1.1	Vector Graphic	3.2.1.1.1(e)	Vector Graphic
2.6.9.1.2	Vector Graphic	3.2.1.1.1(f)	Vector Graphic
2.6.9.1.4(a)	Vector Graphic	3.2.1.1.2(a)	Vector Graphic
2.6.9.1.4(b)	Vector Graphic	3.2.1.1.2(b)	Vector Graphic
2.6.9.1.6(a)	Vector Graphic	3.2.1.1.3(a)	Vector Graphic
2.6.9.1.6(b)	Vector Graphic	3.2.1.1.3(b)	Vector Graphic
2.6.9.1.6(c)	Vector Graphic	3.2.1.1.4	Scanned
2.7.1.0	Vector Graphic	3.2.1.1.5(a)	Vector Graphic
2.7.1.1.1(a)	Vector Graphic	3.2.1.1.5(b)	Vector Graphic
2.7.1.1.1(b)	Vector Graphic	3.2.1.1.6(a)	Vector Graphic
2.7.1.2.6(a)	Vector Graphic	3.2.1.1.6(b)	Vector Graphic
2.7.1.2.6(b)	Vector Graphic	3.2.1.1.6(c)	Vector Graphic
2.7.1.3.1	Vector Graphic	3.2.1.1.6(d)	Vector Graphic
2.7.1.3.2	Vector Graphic	3.2.1.1.6(e)	Vector Graphic
2.7.1.3.3	Vector Graphic	3.2.1.1.6(f)	Vector Graphic
2.7.1.3.4	Vector Graphic	3.2.1.1.6(g)	Vector Graphic
2.7.1.3.6(a)	Vector Graphic	3.2.1.1.6(h)	Vector Graphic
2.7.1.3.6(b)	Vector Graphic	3.2.1.1.6(i)	Vector Graphic
2.7.1.4.6(a)	Vector Graphic	3.2.1.1.6(j)	Vector Graphic
2.7.1.4.6(b)	Vector Graphic	3.2.1.1.6(k)	Vector Graphic
2.7.1.5.1	Vector Graphic	3.2.1.1.6(l)	Vector Graphic
2.7.1.5.2(a)	Vector Graphic	3.2.1.1.6(m)	Vector Graphic
2.7.1.5.2(b)	Vector Graphic	3.2.1.1.6(n)	Vector Graphic
2.7.1.5.3	Vector Graphic	3.2.1.1.6(o)	Vector Graphic
2.7.1.5.4	Vector Graphic	3.2.1.1.6(p)	Vector Graphic
2.7.1.5.6(a)	Vector Graphic	3.2.1.1.6(q)	Vector Graphic
2.7.1.5.6(b)	Vector Graphic	3.2.1.1.6(r)	Vector Graphic
2.7.1.5.6(c)	Vector Graphic	3.2.1.1.6(s)	Vector Graphic
2.7.1.5.6(d)	Vector Graphic	3.2.1.1.6(t)	Vector Graphic
2.8.1.1(a)	Vector Graphic	3.2.1.1.6(u)	Vector Graphic
2.8.1.1(b)	Vector Graphic	3.2.1.1.6(v)	Vector Graphic
2.8.3.2(a)	Vector Graphic	3.2.1.1.8(a)	Scanned
2.8.3.2(b)	Vector Graphic	3.2.1.1.8(b)	Vector Graphic
2.8.3.2(c)	Vector Graphic	3.2.1.1.8(c)	Vector Graphic
2.8.3.2(d)	Scanned	3.2.1.1.8(d)	Vector Graphic
2.8.3.2(e)	Scanned	3.2.1.1.8(e)	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
3.2.2.0	Vector Graphic	3.2.3.1.8(g)	Vector Graphic
3.2.2.1.4	Vector Graphic	3.2.3.1.8(h)	Vector Graphic
3.2.3.0	Vector Graphic	3.2.3.1.8(i)	Vector Graphic
3.2.3.1.1(a)	Vector Graphic	3.2.3.3.1(a)	Vector Graphic
3.2.3.1.1(b)	Vector Graphic	3.2.3.3.1(b)	Vector Graphic
3.2.3.1.1(c)	Vector Graphic	3.2.3.3.1(c)	Vector Graphic
3.2.3.1.1(d)	Vector Graphic	3.2.3.3.1(d)	Vector Graphic
3.2.3.1.1(e)	Vector Graphic	3.2.3.3.5(a)	Vector Graphic
3.2.3.1.1(f)	Vector Graphic	3.2.3.3.5(b)	Vector Graphic
3.2.3.1.2(a)	Vector Graphic	3.2.3.3.6(a)	Vector Graphic
3.2.3.1.2(b)	Vector Graphic	3.2.3.3.6(b)	Vector Graphic
3.2.3.1.3(a)	Vector Graphic	3.2.3.3.6(c)	Vector Graphic
3.2.3.1.3(b)	Vector Graphic	3.2.3.3.6(d)	Vector Graphic
3.2.3.1.4	Scanned	3.2.3.3.6(e)	Vector Graphic
3.2.3.1.5(a)	Vector Graphic	3.2.3.4.1(a)	Vector Graphic
3.2.3.1.5(b)	Vector Graphic	3.2.3.4.1(b)	Vector Graphic
3.2.3.1.6(a)	Vector Graphic	3.2.3.4.1(c)	Vector Graphic
3.2.3.1.6(b)	Vector Graphic	3.2.3.4.1(d)	Vector Graphic
3.2.3.1.6(c)	Vector Graphic	3.2.3.4.1(e)	Scanned
3.2.3.1.6(d)	Vector Graphic	3.2.3.4.1(f)	Scanned
3.2.3.1.6(e)	Vector Graphic	3.2.3.4.2(a)	Vector Graphic
3.2.3.1.6(f)	Vector Graphic	3.2.3.4.2(b)	Vector Graphic
3.2.3.1.6(g)	Vector Graphic	3.2.3.4.3(a)	Vector Graphic
3.2.3.1.6(h)	Vector Graphic	3.2.3.4.3(b)	Vector Graphic
3.2.3.1.6(i)	Vector Graphic	3.2.3.4.5(a)	Vector Graphic
3.2.3.1.6(j)	Vector Graphic	3.2.3.4.5(b)	Vector Graphic
3.2.3.1.6(k)	Vector Graphic	3.2.3.4.6(a)	Vector Graphic
3.2.3.1.6(l)	Vector Graphic	3.2.3.4.6(b)	Vector Graphic
3.2.3.1.6(m)	Vector Graphic	3.2.3.4.6(c)	Vector Graphic
3.2.3.1.6(n)	Vector Graphic	3.2.3.4.6(d)	Vector Graphic
3.2.3.1.6(o)	Vector Graphic	3.2.3.4.6(e)	Vector Graphic
3.2.3.1.6(p)	Vector Graphic	3.2.3.4.6(f)	Vector Graphic
3.2.3.1.6(q)	Vector Graphic	3.2.3.4.6(g)	Vector Graphic
3.2.3.1.6(r)	Vector Graphic	3.2.3.4.6(h)	Vector Graphic
3.2.3.1.6(s)	Vector Graphic	3.2.3.4.6(i)	Vector Graphic
3.2.3.1.6(t)	Vector Graphic	3.2.3.4.6(j)	Vector Graphic
3.2.3.1.6(u)	Vector Graphic	3.2.3.5.1(a)	Vector Graphic
3.2.3.1.6(v)	Vector Graphic	3.2.3.5.1(b)	Vector Graphic
3.2.3.1.6(w)	Vector Graphic	3.2.3.5.1(c)	Vector Graphic
3.2.3.1.6(x)	Vector Graphic	3.2.3.5.1(d)	Vector Graphic
3.2.3.1.6(y)	Vector Graphic	3.2.3.5.2(a)	Vector Graphic
3.2.3.1.6(z)	Vector Graphic	3.2.3.5.2(b)	Vector Graphic
3.2.3.1.6(aa)	Vector Graphic	3.2.3.5.3(a)	Vector Graphic
3.2.3.1.8(a)	Scanned	3.2.3.5.3(b)	Vector Graphic
3.2.3.1.8(b)	Vector Graphic	3.2.3.5.3(c)	Vector Graphic
3.2.3.1.8(c)	Vector Graphic	3.2.3.5.5(a)	Scanned
3.2.3.1.8(d)	Vector Graphic	3.2.3.5.5(b)	Scanned
3.2.3.1.8(e)	Scanned	3.2.3.5.6(a)	Vector Graphic
3.2.3.1.8(f)	Vector Graphic	3.2.3.5.6(b)	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
3.2.3.5.6(c)	Vector Graphic	3.2.11.1.1(c)	Vector Graphic
3.2.3.5.6(d)	Vector Graphic	3.2.11.1.1(d)	Vector Graphic
3.2.3.5.10(a)	Scanned	3.2.11.1.2	Vector Graphic
3.2.3.5.10(b)	Scanned	3.2.11.1.3	Vector Graphic
3.2.4.0	Vector Graphic	3.2.11.1.4	Vector Graphic
3.2.5.1.6(a)	Vector Graphic	3.2.11.1.5	Vector Graphic
3.2.5.1.6(b)	Vector Graphic	3.2.11.1.6(a)	Vector Graphic
3.2.6.1.1(a)	Vector Graphic	3.2.11.1.6(b)	Vector Graphic
3.2.6.1.1(b)	Vector Graphic	3.5.1.0	Vector Graphic
3.2.6.1.6(a)	Scanned	3.5.1.1.1	Vector Graphic
3.2.6.1.6(b)	Scanned	3.5.1.1.4	Vector Graphic
3.2.6.1.9(a)	Scanned	3.5.1.1.5	Vector Graphic
3.2.6.1.9(b)	Scanned	3.5.1.3.1(a)	Vector Graphic
3.2.6.1.9(c)	Scanned	3.5.1.3.1(b)	Vector Graphic
3.2.6.1.9(d)	Scanned	3.5.1.3.1(c)	Vector Graphic
3.2.6.1.9(e)	Scanned	3.5.1.3.1(d)	Vector Graphic
3.2.7.0	Vector Graphic	3.5.1.3.5(a)	Vector Graphic
3.2.7.1.1(a)	Vector Graphic	3.5.1.3.5(b)	Vector Graphic
3.2.7.1.1(b)	Vector Graphic	3.5.1.5.1(a)	Vector Graphic
3.2.7.1.6(a)	Vector Graphic	3.5.1.5.1(b)	Vector Graphic
3.2.7.1.6(b)	Vector Graphic	3.5.1.5.1(c)	Vector Graphic
3.2.7.2.1(a)	Vector Graphic	3.5.1.5.1(d)	Vector Graphic
3.2.7.2.1(b)	Vector Graphic	3.5.1.5.5(a)	Vector Graphic
3.2.7.2.6(a)	Vector Graphic	3.5.1.5.5(b)	Vector Graphic
3.2.7.2.6(b)	Vector Graphic	3.5.2.0	Vector Graphic
3.2.7.2.8(a)	Scanned	3.5.2.1.6(a)	Vector Graphic
3.2.7.2.8(b)	Scanned	3.5.2.1.6(b)	Vector Graphic
3.2.7.2.8(c)	Scanned	3.5.2.1.6(c)	Vector Graphic
3.2.7.2.8(d)	Scanned	3.5.3.1.6(a)	Vector Graphic
3.2.7.3.6(a)	Vector Graphic	3.5.3.1.6(b)	Vector Graphic
3.2.7.3.6(b)	Vector Graphic	3.5.3.1.6(c)	Vector Graphic
3.2.7.3.6(c)	Vector Graphic	3.5.3.2.6(a)	Vector Graphic
3.2.7.3.6(d)	Vector Graphic	3.5.3.2.6(b)	Vector Graphic
3.2.7.3.6(e)	Vector Graphic	3.5.3.2.6(c)	Vector Graphic
3.2.7.4.1(a)	Vector Graphic	3.5.3.3.6(a)	Vector Graphic
3.2.7.4.1(b)	Vector Graphic	3.5.3.3.6(b)	Vector Graphic
3.2.7.4.6(a)	Vector Graphic	3.5.3.3.6(c)	Vector Graphic
3.2.7.4.6(b)	Vector Graphic	3.5.3.4.6	Vector Graphic
3.2.7.4.6(c)	Vector Graphic	3.5.3.7.6	Vector Graphic
3.2.7.4.6(d)	Vector Graphic	3.5.4.1.6	Vector Graphic
3.2.7.4.6(e)	Vector Graphic	3.5.4.2.6	Vector Graphic
3.2.9.1.6(a)	Vector Graphic	3.5.4.3.6(a)	Vector Graphic
3.2.9.1.6(b)	Vector Graphic	3.5.4.3.6(b)	Vector Graphic
3.2.10.1.6(a)	Vector Graphic	3.5.5.0	Vector Graphic
3.2.10.1.6(b)	Vector Graphic	3.5.5.1.6(a)	Vector Graphic
3.2.10.1.6(c)	Vector Graphic	3.5.5.1.6(b)	Vector Graphic
3.2.11.0	Vector Graphic	3.5.5.2.6	Vector Graphic
3.2.11.1.1(a)	Vector Graphic	3.5.5.4.6	Vector Graphic
3.2.11.1.1(b)	Vector Graphic	3.6.1.1.6(a)	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
3.6.1.1.6(b)	Vector Graphic	3.7.3.1.8(f)	Scanned
3.6.2.0	Vector Graphic	3.7.3.1.8(g)	Scanned
3.6.2.2.1(a)	Vector Graphic	3.7.4.1.6(a)	Vector Graphic
3.6.2.2.1(b)	Vector Graphic	3.7.4.1.6(b)	Vector Graphic
3.6.2.2.1(c)	Vector Graphic	3.7.4.1.6(c)	Vector Graphic
3.6.2.2.1(d)	Vector Graphic	3.7.4.1.6(d)	Vector Graphic
3.6.2.2.4	Vector Graphic	3.7.4.1.8(a)	Scanned
3.6.2.2.5(a)	Vector Graphic	3.7.4.1.8(b)	Scanned
3.6.2.2.5(b)	Vector Graphic	3.7.4.2.1	Vector Graphic
3.6.2.2.6(a)	Vector Graphic	3.7.4.2.6(a)	Vector Graphic
3.6.2.2.6(b)	Vector Graphic	3.7.4.2.6(b)	Vector Graphic
3.6.2.2.6(c)	Vector Graphic	3.7.4.2.6(c)	Vector Graphic
3.6.2.2.6(d)	Vector Graphic	3.7.4.2.6(d)	Vector Graphic
3.6.2.2.6(e)	Vector Graphic	3.7.4.2.6(e)	Vector Graphic
3.6.2.2.6(f)	Vector Graphic	3.7.4.2.6(f)	Vector Graphic
3.6.2.2.6(g)	Vector Graphic	3.7.4.2.6(g)	Vector Graphic
3.6.2.2.6(h)	Vector Graphic	3.7.4.2.6(h)	Vector Graphic
3.6.2.2.6(i)	Vector Graphic	3.7.4.2.6(i)	Vector Graphic
3.6.2.2.6(j)	Vector Graphic	3.7.4.2.6(j)	Vector Graphic
3.6.2.2.6(k)	Vector Graphic	3.7.4.2.8(a)	Scanned
3.6.2.2.6(l)	Vector Graphic	3.7.4.2.8(b)	Vector Graphic
3.6.2.2.6(m)	Vector Graphic	3.7.4.2.8(c)	Vector Graphic
3.6.2.2.6(n)	Vector Graphic	3.7.4.2.8(d)	Vector Graphic
3.6.2.2.6(o)	Vector Graphic	3.7.4.2.8(e)	Scanned
3.6.2.2.8	Vector Graphic	3.7.4.2.8(f)	Scanned
3.6.3.0	Vector Graphic	3.7.4.2.8(g)	Scanned
3.7.1.1.1	Vector Graphic	3.7.4.2.8(h)	Scanned
3.7.1.1.6(a)	Vector Graphic	3.7.4.2.8(i)	Scanned
3.7.1.1.6(b)	Vector Graphic	3.7.4.2.8(j)	Scanned
3.7.1.1.6(c)	Vector Graphic	3.7.4.2.8(k)	Scanned
3.7.1.1.6(d)	Vector Graphic	3.7.4.2.8(l)	Scanned
3.7.1.2.6(a)	Vector Graphic	3.7.4.2.9(a)	Scanned
3.7.1.2.6(b)	Vector Graphic	3.7.4.2.9(b)	Scanned
3.7.1.2.6(c)	Vector Graphic	3.7.4.2.9(c)	Scanned
3.7.1.2.6(d)	Vector Graphic	3.7.4.3.6(a)	Vector Graphic
3.7.2.0	Vector Graphic	3.7.4.3.6(b)	Vector Graphic
3.7.3.1.1	Vector Graphic	3.7.4.3.6(c)	Vector Graphic
3.7.3.1.6(a)	Vector Graphic	3.7.4.3.6(d)	Vector Graphic
3.7.3.1.6(b)	Vector Graphic	3.7.4.3.6(e)	Vector Graphic
3.7.3.1.6(c)	Vector Graphic	3.7.4.3.6(f)	Vector Graphic
3.7.3.1.6(d)	Vector Graphic	3.7.4.3.8(a)	Scanned
3.7.3.1.6(e)	Vector Graphic	3.7.4.3.8(b)	Scanned
3.7.3.1.6(f)	Vector Graphic	3.7.6.0	Vector Graphic
3.7.3.1.6(g)	Vector Graphic	3.7.6.1.1(a)	Scanned
3.7.3.1.8(a)	Scanned	3.7.6.1.1(b)	Scanned
3.7.3.1.8(b)	Scanned	3.7.6.1.1(c)	Vector Graphic
3.7.3.1.8(c)	Scanned	3.7.6.1.1(d)	Vector Graphic
3.7.3.1.8(d)	Scanned	3.7.6.1.2(a)	Vector Graphic
3.7.3.1.8(e)	Scanned	3.7.6.1.2(b)	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
3.7.6.1.3(a)	Vector Graphic	3.7.6.2.10(b)	Scanned
3.7.6.1.3(b)	Vector Graphic	3.7.7.1.6(a)	Vector Graphic
3.7.6.1.4	Vector Graphic	3.7.7.1.6(b)	Vector Graphic
3.7.6.1.5(a)	Vector Graphic	3.7.7.1.6(c)	Vector Graphic
3.7.6.1.5(b)	Vector Graphic	3.7.7.1.6(d)	Vector Graphic
3.7.6.1.6(a)	Vector Graphic	3.7.7.2.6(a)	Vector Graphic
3.7.6.1.6(b)	Vector Graphic	3.7.7.2.6(b)	Vector Graphic
3.7.6.1.6(c)	Vector Graphic	3.7.7.2.6(c)	Vector Graphic
3.7.6.1.6(d)	Vector Graphic	3.7.7.2.6(d)	Vector Graphic
3.7.6.1.6(e)	Vector Graphic	3.7.7.2.8(a)	Vector Graphic
3.7.6.1.6(f)	Vector Graphic	3.7.7.2.8(b)	Vector Graphic
3.7.6.1.6(g)	Vector Graphic	3.7.7.2.8(c)	Vector Graphic
3.7.6.1.6(h)	Vector Graphic	3.7.8.1.6(a)	Vector Graphic
3.7.6.1.6(i)	Vector Graphic	3.7.8.1.6(b)	Vector Graphic
3.7.6.1.6(j)	Vector Graphic	3.7.8.1.8(a)	Vector Graphic
3.7.6.1.6(k)	Vector Graphic	3.7.8.1.8(b)	Vector Graphic
3.7.6.1.6(l)	Vector Graphic	3.7.8.1.8(c)	Vector Graphic
3.7.6.1.6(m)	Vector Graphic	3.7.8.1.8(d)	Vector Graphic
3.7.6.1.6(n)	Vector Graphic	3.7.8.2.6(a)	Vector Graphic
3.7.6.1.6(o)	Vector Graphic	3.7.8.2.6(b)	Vector Graphic
3.7.6.1.6(p)	Vector Graphic	3.7.8.2.6(c)	Vector Graphic
3.7.6.1.6(q)	Vector Graphic	3.7.8.2.6(d)	Vector Graphic
3.7.6.1.8(a)	Scanned	3.7.8.2.6(e)	Vector Graphic
3.7.6.1.8(b)	Scanned	3.7.8.2.6(f)	Vector Graphic
3.7.6.1.8(c)	Scanned	3.7.8.2.8(a)	Scanned
3.7.6.1.8(d)	Vector Graphic	3.7.8.2.8(b)	Scanned
3.7.6.1.8(e)	Scanned	3.7.9.1.6(a)	Vector Graphic
3.7.6.1.8(f)	Vector Graphic	3.7.9.1.6(b)	Vector Graphic
3.7.6.1.8(g)	Scanned	3.7.9.1.6(c)	Vector Graphic
3.7.6.1.8(h)	Vector Graphic	3.7.10.1.6(a)	Vector Graphic
3.7.6.1.9	Scanned	3.7.10.1.6(b)	Vector Graphic
3.7.6.1.10(a)	Scanned	3.7.10.1.6(c)	Vector Graphic
3.7.6.1.10(b)	Scanned	3.7.10.1.6(d)	Vector Graphic
3.7.6.1.10(c)	Scanned	3.7.10.1.6(e)	Vector Graphic
3.7.6.1.10(d)	Scanned	3.7.10.1.6(f)	Vector Graphic
3.7.6.1.10(e)	Scanned	3.7.10.1.6(g)	Vector Graphic
3.7.6.1.10(f)	Scanned	3.7.10.1.8(a)	Scanned
3.7.6.1.10(g)	Scanned	3.7.10.1.8(b)	Vector Graphic
3.7.6.1.10(h)	Scanned	3.7.10.1.8(c)	Scanned
3.7.6.2.6(a)	Vector Graphic	3.7.10.1.10(a)	Scanned
3.7.6.2.6(b)	Vector Graphic	3.7.10.1.10(b)	Scanned
3.7.6.2.6(c)	Vector Graphic	3.7.10.1.10(c)	Scanned
3.7.6.2.6(d)	Vector Graphic	3.7.10.1.10(d)	Scanned
3.7.6.2.6(e)	Vector Graphic	3.7.10.2.6(a)	Vector Graphic
3.7.6.2.6(f)	Vector Graphic	3.7.10.2.6(b)	Vector Graphic
3.7.6.2.9(a)	Scanned	3.7.10.2.8(a)	Scanned
3.7.6.2.9(b)	Scanned	3.7.10.2.8(b)	Scanned
3.7.6.2.9(c)	Scanned	3.7.10.2.9(a)	Scanned
3.7.6.2.10(a)	Scanned	3.7.10.2.9(b)	Scanned

Figure No.	Current Form	Figure No.	Current Form
3.7.10.3.6(a)	Vector Graphic	4.2.3.2.8(b)	Scanned
3.7.10.3.6(b)	Vector Graphic	4.2.3.2.8(c)	Scanned
3.7.10.3.6(c)	Vector Graphic	4.3.2.1.4	Vector Graphic
3.7.10.3.6(d)	Vector Graphic	4.3.2.1.6	Vector Graphic
3.7.10.3.6(e)	Vector Graphic	4.3.3.0	Vector Graphic
3.7.10.3.6(f)	Vector Graphic	4.3.3.1.1(a)	Vector Graphic
3.7.10.3.6(g)	Vector Graphic	4.3.3.1.1(b)	Vector Graphic
3.7.10.3.6(h)	Vector Graphic	4.3.3.1.1(c)	Vector Graphic
3.7.10.3.6(i)	Vector Graphic	4.3.3.1.4	Vector Graphic
3.7.10.3.6(j)	Vector Graphic	4.3.3.1.6(a)	Vector Graphic
3.7.10.3.6(k)	Vector Graphic	4.3.3.1.6(b)	Vector Graphic
3.7.10.3.6(l)	Vector Graphic	4.3.4.0	Vector Graphic
3.7.10.3.10(a)	Scanned	4.3.4.1.1(a)	Scanned
3.7.10.3.10(b)	Scanned	4.3.4.1.1(b)	Scanned
3.8.1.0	Vector Graphic	4.3.4.1.1(C)	Scanned
3.8.1.1.6	Vector Graphic	4.3.4.1.6	Vector Graphic
3.8.1.1.8(a)	Scanned	4.3.5.1.1	Scanned
3.8.1.1.8(b)	Scanned	4.3.5.1.4	Scanned
3.8.1.1.8(c)	Scanned	4.3.5.1.6	Vector Graphic
3.9.2.0	Vector Graphic	4.3.6.0	Scanned
3.9.4.0	Vector Graphic	4.3.6.1.1	Scanned
3.9.5.1.6(a)	Vector Graphic	4.3.6.1.4	Scanned
3.9.5.1.6(b)	Vector Graphic	4.3.6.1.6(a)	Scanned
3.9.6.1.6	Vector Graphic	4.3.6.1.6(b)	Vector Graphic
3.9.7.1.6	Vector Graphic	4.4.2.3(a)	Scanned
3.11.1.1.1	Vector Graphic	4.4.2.3(b)	Scanned
3.11.2.3(a)	Scanned	4.4.3.2	Scanned
3.11.2.3(b)	Scanned	5.2.1.0	Scanned
3.11.3.2(a)	Scanned	5.2.1.1.1(a)	Scanned
3.11.3.2(b)	Vector Graphic	5.2.1.1.1(b)	Scanned
3.11.3.2(c)	Scanned	5.2.1.1.2(a)	Scanned
3.11.3.2(d)	Scanned	5.2.1.1.2(b)	Scanned
3.11.3.2(e)	Vector Graphic	5.2.1.1.3(a)	Scanned
3.11.3.2(f)	Vector Graphic	5.2.1.1.3(b)	Scanned
3.11.3.2(g)	Vector Graphic	5.2.1.1.6(a)	Scanned
4.2.1.0	Vector Graphic	5.2.1.1.6(b)	Scanned
4.2.1.1.4	Scanned	5.3.1.0	Vector Graphic
4.2.1.1.6	Vector Graphic	5.3.1.1.1	Scanned
4.2.1.2.1	Scanned	5.3.1.1.2	Scanned
4.2.1.2.2	Scanned	5.3.1.1.3	Scanned
4.2.1.2.3	Scanned	5.3.1.1.4	Scanned
4.2.1.2.4	Scanned	5.3.1.1.5	Scanned
4.2.1.2.6	Vector Graphic	5.3.1.1.9(a)	Scanned
4.2.1.4.8(a)	Vector Graphic	5.3.1.1.9(b)	Scanned
4.2.1.4.8(b)	Scanned	5.3.1.1.9(c)	Scanned
4.2.3.0	Vector Graphic	5.3.2.0	Scanned
4.2.3.2.6(a)	Vector Graphic	5.3.2.1.1	Scanned
4.2.3.2.6(b)	Scanned	5.3.2.1.4	Scanned
4.2.3.2.8(a)	Scanned	5.3.2.1.6(a)	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
5.3.2.1.6(b)	Vector Graphic	5.4.1.2.8(b)	Scanned
5.3.2.2.1	Scanned	5.4.1.2.8(c)	Scanned
5.3.2.2.6(a)	Vector Graphic	5.4.1.2.8(d)	Scanned
5.3.2.2.6(b)	Vector Graphic	5.4.1.2.8(e)	Scanned
5.3.2.2.8(a)	Scanned	5.4.1.2.8(f)	Scanned
5.3.2.2.8(b)	Scanned	5.4.1.2.8(g)	Scanned
5.3.2.2.8(c)	Scanned	5.4.1.2.8(h)	Scanned
5.3.2.2.8(d)	Scanned	5.4.1.2.8(i)	Scanned
5.3.2.2.8(e)	Scanned	5.4.2.0	Scanned
5.3.2.2.8(f)	Scanned	5.4.2.1.1(a)	Scanned
5.3.3.0	Scanned	5.4.2.1.1(b)	Scanned
5.3.3.1.1	Scanned	5.4.2.1.2(a)	Scanned
5.3.3.1.2	Scanned	5.4.2.1.2(b)	Scanned
5.3.3.1.4	Scanned	5.4.2.1.3(a)	Scanned
5.3.3.1.6(a)	Vector Graphic	5.4.2.1.3(b)	Scanned
5.3.3.1.6(b)	Vector Graphic	5.4.2.1.6(a)	Vector Graphic
5.3.3.1.6(c)	Scanned	5.4.2.1.6(b)	Vector Graphic
5.4.1.0	Vector Graphic	5.4.2.1.6(c)	Scanned
5.4.1.1.1	Vector Graphic	5.4.2.1.8(a)	Scanned
5.4.1.1.2	Scanned	5.4.2.1.8(b)	Scanned
5.4.1.1.3	Scanned	5.4.2.2.1	Scanned
5.4.1.1.4	Scanned	5.4.2.2.2	Scanned
5.4.1.1.5	Scanned	5.4.3.1(a)	Vector Graphic
5.4.1.1.6(a)	Vector Graphic	5.4.3.1(b)	Vector Graphic
5.4.1.1.6(b)	Vector Graphic	5.4.3.1(c)	Vector Graphic
5.4.1.1.6(c)	Vector Graphic	5.4.3.2(a)	Scanned
5.4.1.1.6(d)	Scanned	5.4.3.2(b)	Scanned
5.4.1.1.8(a)	Scanned	5.4.3.3	Scanned
5.4.1.1.8(b)	Scanned	5.5.1.0	Scanned
5.4.1.1.8(c)	Scanned	5.5.1.1.1	Scanned
5.4.1.1.8(d)	Scanned	5.5.1.1.2	Scanned
5.4.1.1.8(e)	Scanned	5.5.1.1.3(a)	Scanned
5.4.1.1.8(f)	Scanned	5.5.1.1.3(b)	Scanned
5.4.1.1.8(g)	Scanned	5.5.1.1.4	Scanned
5.4.1.1.9	Scanned	5.5.1.1.6	Vector Graphic
5.4.1.2.1	Scanned	5.5.1.1.8(a)	Scanned
5.4.1.2.2	Scanned	5.5.1.1.8(b)	Scanned
5.4.1.2.3	Scanned	5.5.1.1.8(c)	Scanned
5.4.1.2.4	Scanned	5.5.1.1.8(d)	Scanned
5.4.1.2.6(a)	Vector Graphic	5.5.1.2.1	Scanned
5.4.1.2.6(b)	Vector Graphic	5.5.1.2.2	Scanned
5.4.1.2.6(c)	Vector Graphic	5.5.1.2.3	Scanned
5.4.1.2.6(d)	Vector Graphic	5.5.1.2.4	Scanned
5.4.1.2.6(e)	Vector Graphic	5.5.1.2.6	Vector Graphic
5.4.1.2.6(f)	Vector Graphic	5.5.1.2.8(a)	Scanned
5.4.1.2.6(g)	Vector Graphic	5.5.1.2.8(b)	Scanned
5.4.1.2.6(h)	Scanned	5.5.1.2.8(c)	Scanned
5.4.1.2.7	Scanned	5.5.2.0	Scanned
5.4.1.2.8(a)	Scanned	5.5.2.1.6(a)	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
5.5.2.1.6(b)	Vector Graphic	6.3.4.1.6(c)	Scanned
5.5.3.1.6	Vector Graphic	6.3.5.0	Vector Graphic
5.5.3.2.6	Vector Graphic	6.3.5.1.1	Scanned
5.6.1.1.1	Scanned	6.3.5.1.4(a)	Scanned
6.2.1.0	Scanned	6.3.5.1.4(b)	Scanned
6.2.1.1.1	Scanned	6.3.5.1.4(c)	Scanned
6.2.1.1.3	Scanned	6.3.5.1.6(a)	Vector Graphic
6.2.1.1.4(a)	Scanned	6.3.5.1.6(b)	Vector Graphic
6.2.1.1.4(b)	Scanned	6.3.5.1.6(c)	Vector Graphic
6.2.1.1.4(c)	Scanned	6.3.5.1.6(d)	Scanned
6.2.1.1.8(a)	Scanned	6.3.5.1.7(a)	Scanned
6.2.1.1.8(b)	Scanned	6.3.5.1.7(b)	Scanned
6.2.1.1.8(c)	Scanned	6.3.5.1.7(c)	Scanned
6.2.1.1.8(d)	Scanned	6.3.5.1.7(d)	Vector Graphic
6.2.1.1.8(e)	Scanned	6.3.5.1.7(e)	Vector Graphic
6.2.2.0	Scanned	6.3.5.1.8(a)	Vector Graphic
6.2.2.1.1(a)	Scanned	6.3.5.1.8(b)	Vector Graphic
6.2.2.1.1(b)	Scanned	6.3.5.1.8(c)	Vector Graphic
6.2.2.1.4(a)	Scanned	6.3.5.1.8(d)	Vector Graphic
6.2.2.1.4(b)	Scanned	6.3.5.1.8(e)	Vector Graphic
6.3.1.0	Scanned	6.3.5.1.8(f)	Vector Graphic
6.3.1.1.1	Scanned	6.3.5.1.8(g)	Vector Graphic
6.3.1.1.4	Scanned	6.3.5.1.9(a)	Vector Graphic
6.3.1.1.6(a)	Vector Graphic	6.3.5.1.9(b)	Scanned
6.3.1.1.6(b)	Vector Graphic	6.3.5.1.9(c)	Scanned
6.3.2.0	Scanned	6.3.6.0	Scanned
6.3.2.1.1	Scanned	6.3.6.1.1	Scanned
6.3.2.1.2	Scanned	6.3.6.1.2	Scanned
6.3.2.1.3	Scanned	6.3.6.1.3	Scanned
6.3.2.1.4	Scanned	6.3.6.2.1(a)	Scanned
6.3.3.0	Scanned	6.3.6.2.1(b)	Scanned
6.3.3.1.1(a)	Scanned	6.3.6.2.4(a)	Scanned
6.3.3.1.1(b)	Scanned	6.3.6.2.4(b)	Scanned
6.3.3.1.4(a)	Scanned	6.3.7.0	Scanned
6.3.3.1.4(b)	Scanned	6.3.7.1.1	Vector Graphic
6.3.3.1.6(a)	Vector Graphic	6.3.7.1.2	Vector Graphic
6.3.3.1.6(b)	Vector Graphic	6.3.7.1.3(a)	Scanned
6.3.3.1.6(c)	Vector Graphic	6.3.7.1.3(b)	Scanned
6.3.3.1.6(d)	Vector Graphic	6.3.7.1.4	Scanned
6.3.3.1.8(a)	Scanned	6.3.7.1.5	Scanned
6.3.3.1.8(b)	Scanned	6.3.7.1.7	Scanned
6.3.3.1.8(c)	Scanned	6.3.8.0	Scanned
6.3.3.1.8(d)	Scanned	6.3.8.1.1	Scanned
6.3.4.0	Vector Graphic	6.3.8.1.4	Scanned
6.3.4.1.1	Vector Graphic	6.3.8.1.5(a)	Scanned
6.3.4.1.4	Vector Graphic	6.3.8.1.5(b)	Scanned
6.3.4.1.5	Vector Graphic	6.3.8.1.6(a)	Scanned
6.3.4.1.6(a)	Vector Graphic	6.3.8.1.6(b)	Scanned
6.3.4.1.6(b)	Vector Graphic	6.3.9.0(a)	Vector Graphic

Figure No.	Current Form	Figure No.	Current Form
6.3.9.0(b)	Vector Graphic	7.5.1.1.6(h)	Vector Graphic
6.3.9.0(c)	Vector Graphic	7.5.1.1.6(i)	Vector Graphic
6.3.9.0(d)	Vector Graphic	7.5.1.1.6(j)	Vector Graphic
6.3.9.0(e)	Vector Graphic	7.5.1.1.6(k)	Vector Graphic
6.4.1.0	Scanned	7.5.1.1.6(l)	Vector Graphic
6.4.1.1.1	Vector Graphic	7.5.2.1.6(a)	Vector Graphic
6.4.1.1.2	Vector Graphic	7.5.2.1.6(b)	Vector Graphic
6.4.1.1.3	Vector Graphic	7.5.2.1.6(c)	Vector Graphic
6.4.1.1.4(a)	Vector Graphic	7.5.2.1.6(d)	Vector Graphic
6.4.1.1.4(b)	Scanned	7.5.2.1.6(e)	Vector Graphic
6.4.1.1.5	Scanned	7.5.2.1.6(f)	Vector Graphic
6.4.1.1.7	Scanned	7.5.2.1.6(g)	Vector Graphic
6.4.2.0	Scanned	7.5.2.1.6(h)	Vector Graphic
6.4.2.1.1(a)	Scanned	7.5.2.1.6(i)	Vector Graphic
6.4.2.1.1(b)	Scanned	7.5.2.1.6(j)	Vector Graphic
6.4.2.1.2	Scanned	8.2.1	Scanned
6.4.2.1.4(a)	Scanned	8.2.2.3.1.1(a)	Scanned
6.4.2.1.4(b)	Scanned	8.2.2.3.1.1(b)	Scanned
6.4.2.1.4(c)	Scanned	8.2.2.3.1.1(c)	Scanned
6.4.2.1.5	Scanned	8.2.2.3.2.1	Scanned
6.4.2.1.6(a)	Vector Graphic	8.2.2.3.2.2(a)	Scanned
6.4.2.1.6(b)	Vector Graphic	8.2.2.3.2.2(b)	Scanned
6.4.2.1.8(a)	Scanned	8.2.2.3.2.2(c)	Scanned
6.4.2.1.8(b)	Scanned	8.2.2.3.2.2(d)	Scanned
6.4.2.1.8(c)	Scanned	8.2.2.3.2.2(e)	Scanned
6.4.2.1.8(d)	Scanned	9.2.3	Scanned
7.2.1.0	Vector Graphic	9.2.4	Scanned
7.2.1.1.1	Vector Graphic	9.2.6	Scanned
7.2.1.1.4	Vector Graphic	9.2.11	Scanned
7.3.2.0	Vector Graphic	9.2.12	Scanned
7.3.2.1.6(a)	Vector Graphic	9.2.15(a)	Scanned
7.3.2.1.6(b)	Vector Graphic	9.2.15(b)	Scanned
7.3.2.2.6	Vector Graphic	9.3.1.1.2	Scanned
7.4.1.0	Scanned	9.3.1.1.3(a)	Scanned
7.4.1.1.1	Scanned	9.3.1.1.3(b)	Scanned
7.4.1.1.4(a)	Scanned	9.3.1.2	Scanned
7.4.1.1.4(b)	Scanned	9.3.1.3	Scanned
7.4.1.1.5	Scanned	9.3.1.4(a)	Scanned
7.4.1.1.6	Vector Graphic	9.3.1.4(b)	Scanned
7.4.2.0	Scanned	9.3.1.5	Scanned
7.4.2.1.4	Scanned	9.3.1.6.1	Scanned
7.4.2.1.6	Vector Graphic	9.3.1.6.2	Vector Graphic
7.5.1.1.6(a)	Vector Graphic	9.3.2.3(a)	Scanned
7.5.1.1.6(b)	Vector Graphic	9.3.2.3(b)	Scanned
7.5.1.1.6(c)	Vector Graphic	9.3.2.3(c)	Vector Graphic
7.5.1.1.6(d)	Vector Graphic	9.3.2.4	Scanned
7.5.1.1.6(e)	Vector Graphic	9.3.2.5(a)	Scanned
7.5.1.1.6(f)	Vector Graphic	9.3.2.5(b)	Vector Graphic
7.5.1.1.6(g)	Vector Graphic	9.3.2.5(c)	Vector Graphic

Figure No.	Current Form
9.3.2.5(d)	Vector Graphic
9.3.2.7(a)	Scanned
9.3.2.7(b)	Scanned
9.3.2.7(c)	Scanned
9.3.4.1(a)	Scanned
9.3.4.1(b)	Scanned
9.3.4.1(c)	Scanned
9.3.4.1(d)	Scanned
9.3.4.3	Scanned
9.3.4.4	Scanned
9.3.4.5	Scanned
9.3.4.7	Scanned
9.3.4.10(a)	Scanned
9.3.4.10(b)	Scanned
9.3.4.10(c)	Scanned
9.3.4.12(a)	Scanned
9.3.4.12(b)	Scanned
9.3.4.13	Scanned
9.3.4.16(a)	Scanned
9.3.4.17(a)	Scanned
9.3.4.17(b)	Scanned
9.3.4.17(c)	Scanned
9.3.4.17(d)	Scanned
9.3.4.17(e)	Scanned
9.3.4.17(f)	Scanned
9.3.4.17(g)	Scanned
9.3.4.17(h)	Scanned
9.3.5.1(a)	Scanned
9.3.5.1(b)	Scanned
9.3.5.2	Scanned
9.3.5.6	Scanned
9.3.6.2	Scanned
9.3.6.7	Scanned
9.3.6.8(a)	Scanned
9.3.6.8(b)	Scanned
9.3.6.8(c)	Scanned
9.3.6.8(d)	Scanned
9.4.1.3	Scanned
9.4.1.3.4(a)	Scanned
9.4.1.3.4(b)	Scanned
9.4.1.3.4(c)	Scanned
9.4.1.3.4(d)	Scanned
9.4.1.3.4(e)	Scanned
9.4.1.5.2(a)	Scanned
9.4.1.5.2(b)	Scanned
9.4.1.5.2(c)	Scanned
9.4.1.5.2(d)	Scanned
9.4.1.5.2(e)	Scanned
9.4.1.5.2(f)	Scanned

Figure No.	Current Form
9.4.1.5.2(g)	Scanned
9.4.1.5.2(h)	Scanned
9.4.1.5.3	Scanned
9.4.1.6	Scanned
9.4.1.7.2	Scanned
9.4.1.7.2, cont.	Scanned
9.4.2.2	Scanned
9.4.2.3.2	Scanned
9.4.2.3.5(a)	Scanned
9.4.2.3.5(b)	Scanned
9.4.2.5.2	Scanned
9.4.2.5.3	Scanned
9.5.1.3	Scanned
9.5.1.5.1(a)	Scanned
9.5.1.5.1(b)	Scanned
9.5.1.5.1(c)	Scanned
9.5.1.5.3	Scanned
9.6.3	Scanned
A.1	Scanned